First Offshore Comparative Resource and Energy Yield Assessment Procedures (CREYAP)

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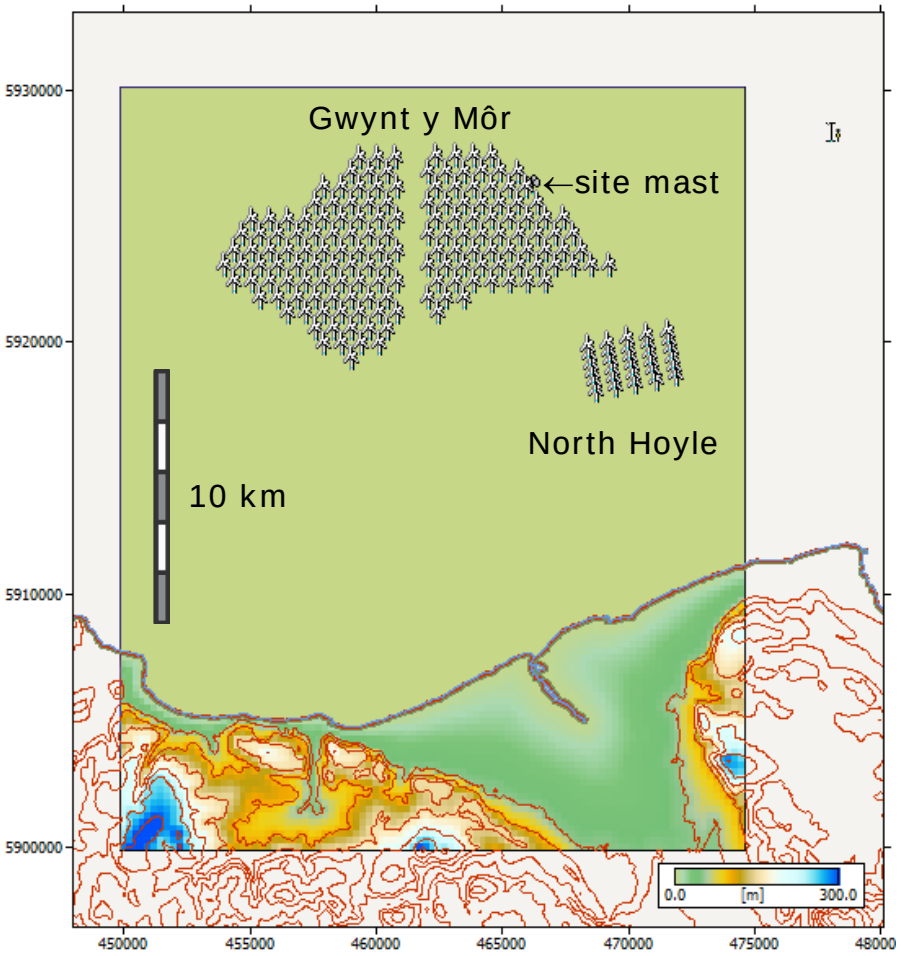
DTU Wind Energy

EWEA Offshore 2013
Frankfurt, Germany

- The data pack used for the offshore comparison was made available by Renewable Energy Systems Ltd. (RES); thanks to Mike Anderson and Tom Young.
- The 38 sets of results were submitted by 37 organisations from 13 countries; thanks to all of the teams for making the comparison and this presentation possible!
- Thanks to Tim Robinson and EWEA team for arranging the 2013 offshore CREYAP.

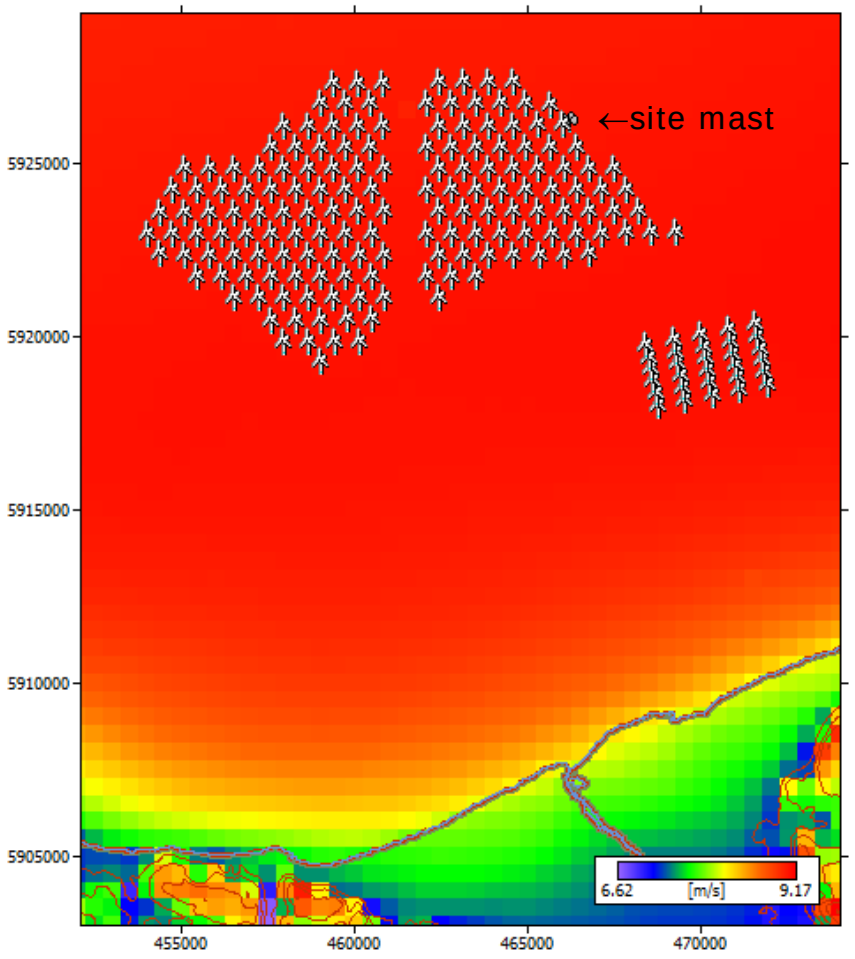
First offshore CREYAP results

- Introduction
- Case study wind farm
  - Wind farm and turbine data
  - Wind-climatological inputs
  - Topographical inputs
- Comparisons of results & methods
  - The prediction process
  - Long-term wind climate
  - Wind farm energy yields
  - Effect upon North Hoyle
  - Export system constraint
- Summary and conclusions
- Appendices
  - Team results and statistics ↓



Gwynt y Môr wind farm

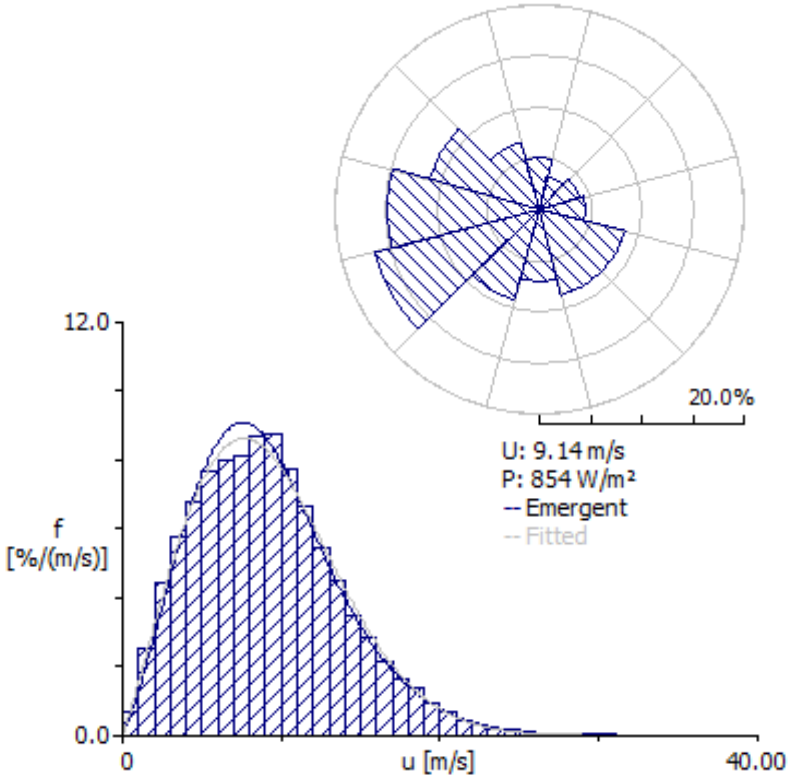
- 160 wind turbines (576 MW)
  - Rated power: 3.6 MW
  - Hub height: 79.4 m
  - Rotor diameter: 107 m
  - Spacing: regular, 6-7 *D*
  - Air density: 1.23 kg m^{-3}
- Site meteorological mast
  - Wind speed @ 85 m
  - Std. deviation @ 85 m
  - Wind direction @ 82 m
  - Air temperature @ 20 m
  - Barometric pressure @ 20 m
- Site topographical data
  - Participants choice



Wind-climatological inputs

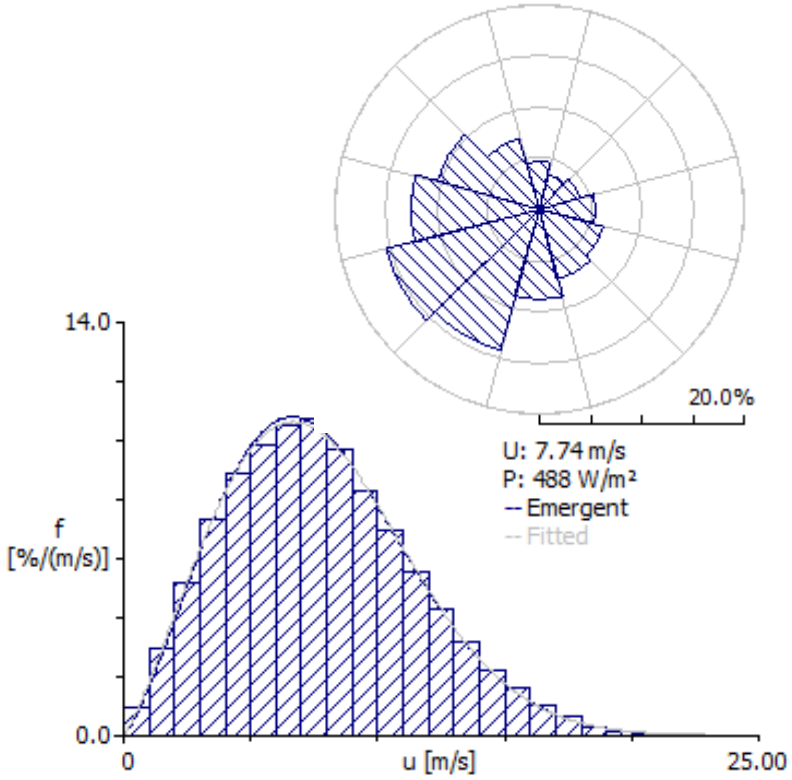
Site meteorological mast

- 2.6 years of 10-min mean data



MERRA reanalysis data

- 11.4 years of hourly mean data



Data analysis & presentation

Data material

- Result spreadsheets from 38 teams

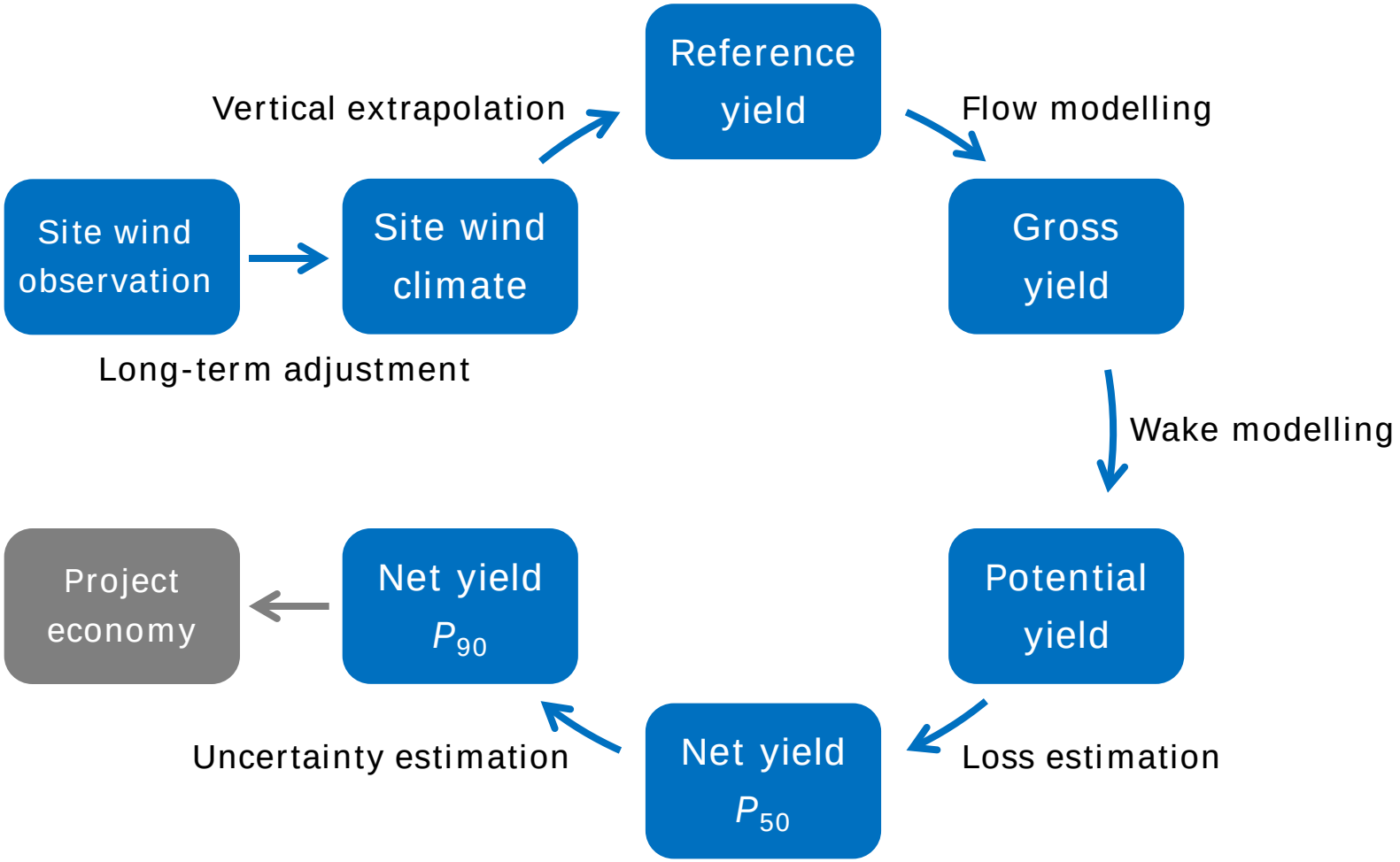
Data analysis

- Quality control and reformatting
- Consistent calculations (loss factors)
- Calculation of missing numbers – but no comprehensive reanalysis!

Data presentation

- Comparison of methods and models
  - Non-parametric box-whisker plot
  - Statistics (median, quartiles, IQR)
- Overall distribution of all results
  - Normal distribution fitted to the results
  - Statistics (mean, standard deviation, coefficient of variation)
- Team results for each parameter (see appendix)

Steps in the energy yield prediction process



Comparison of air density ρ @ hub height

Data points used = 36 (of 38)

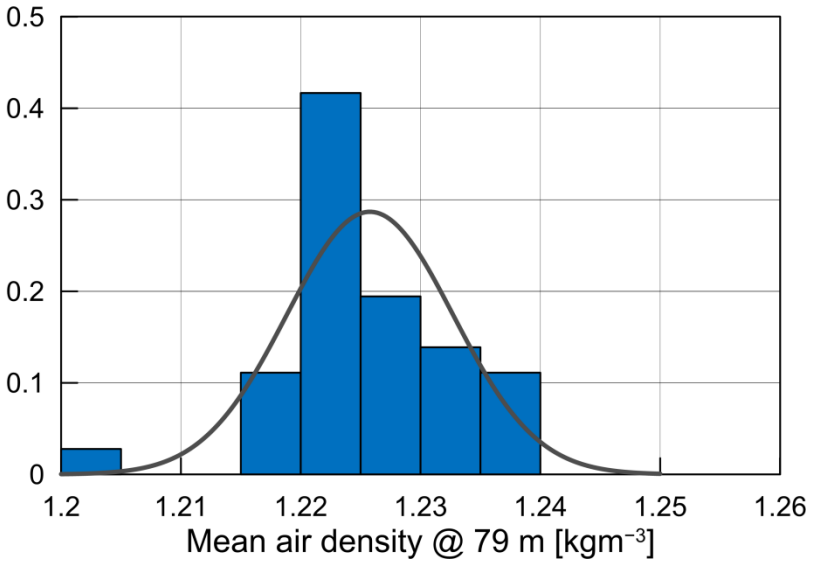
Mean air density = 1.226 kgm^{-3}

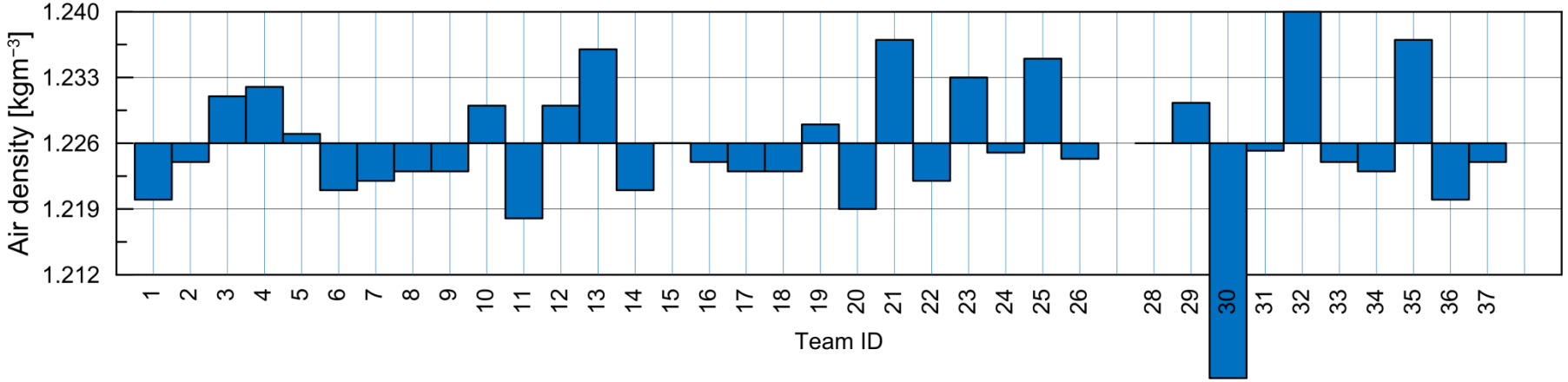
Standard deviation = 0.007 kgm^{-3}

Coefficient of variation = 0.6%

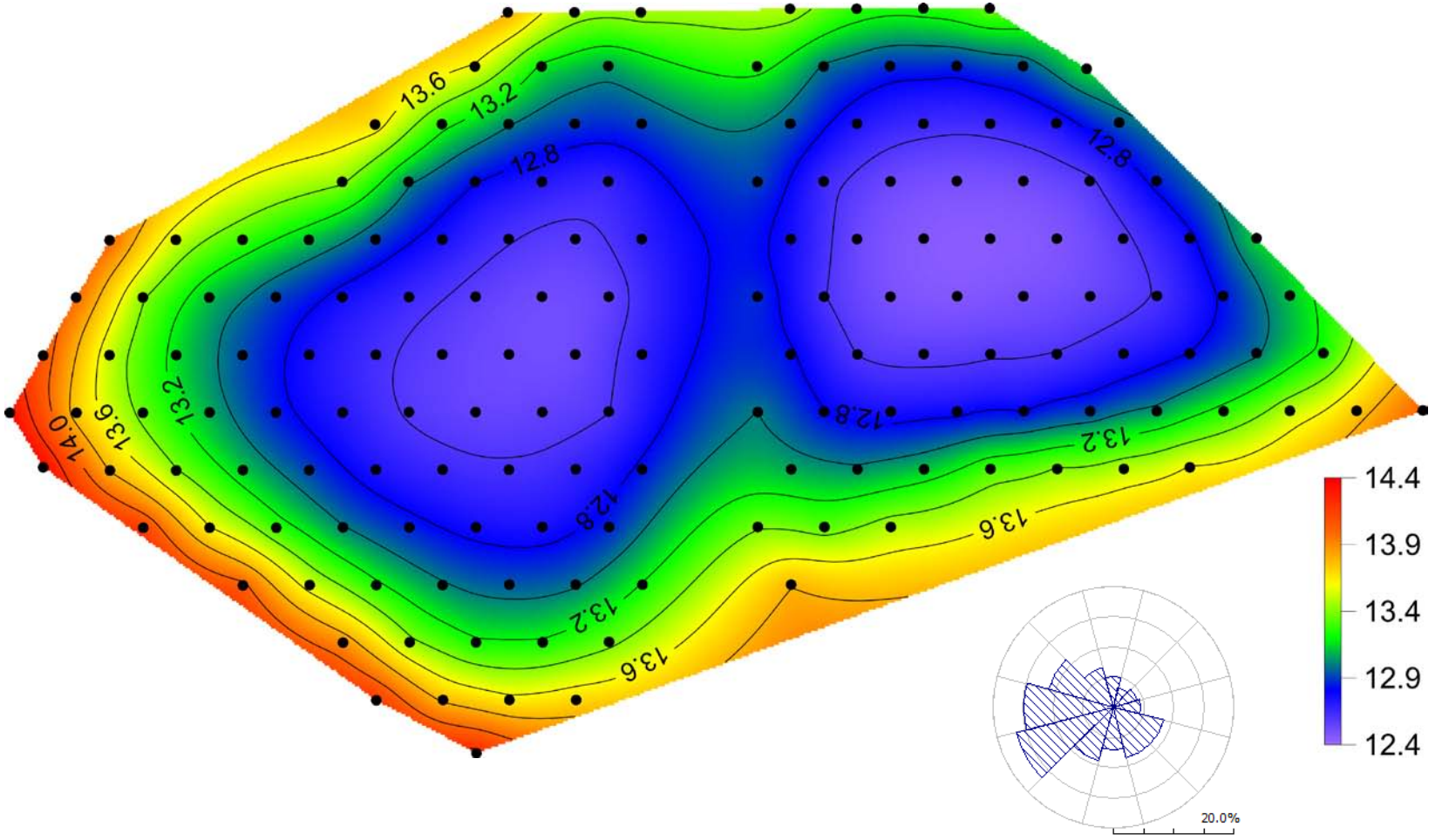
Range = 1.201 to 1.240 kgm^{-3} (3%)

AEP sensitivity ~ 0.5% for 1% in ρ

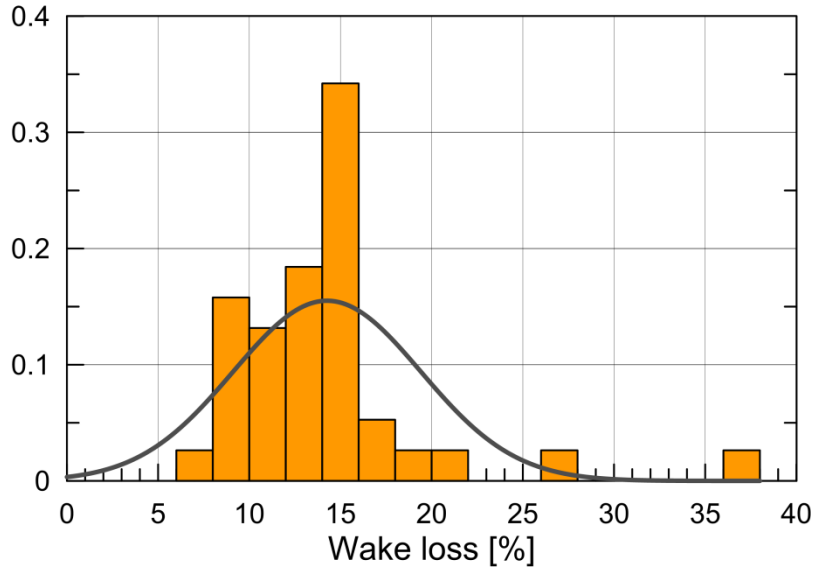




Turbine sites: mean potential AEP [GWhy^{-1}]



Predicted wind farm wake losses



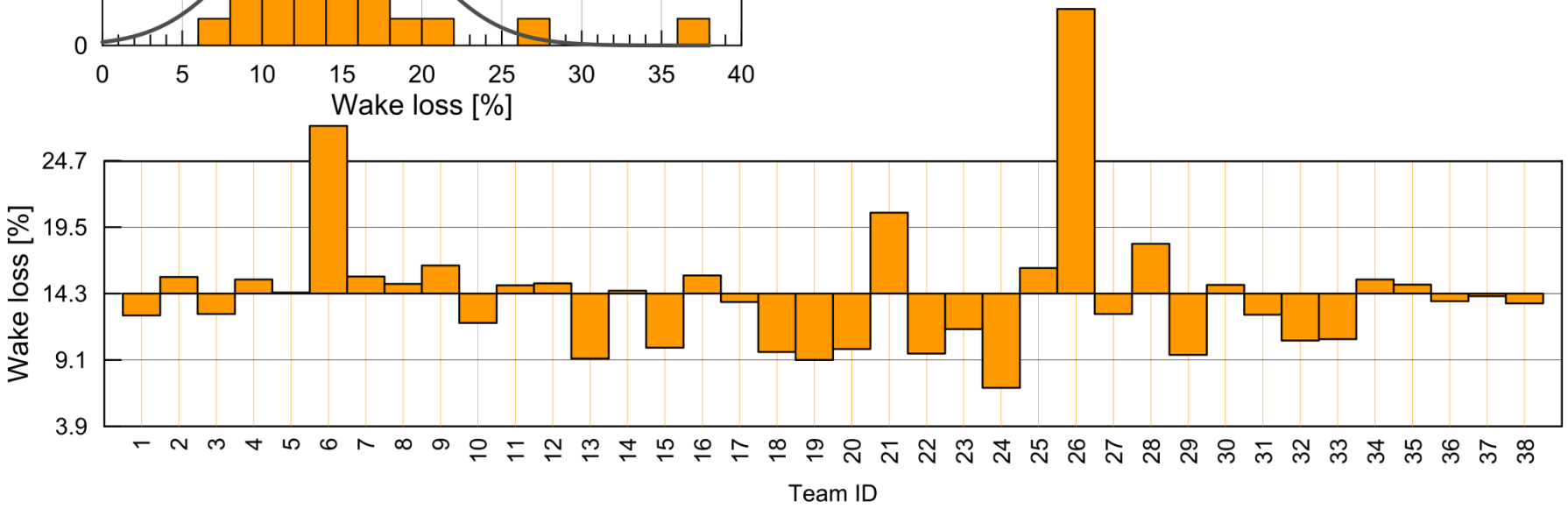
Data points used = 38 (of 38)

Mean wake loss = 14.3%

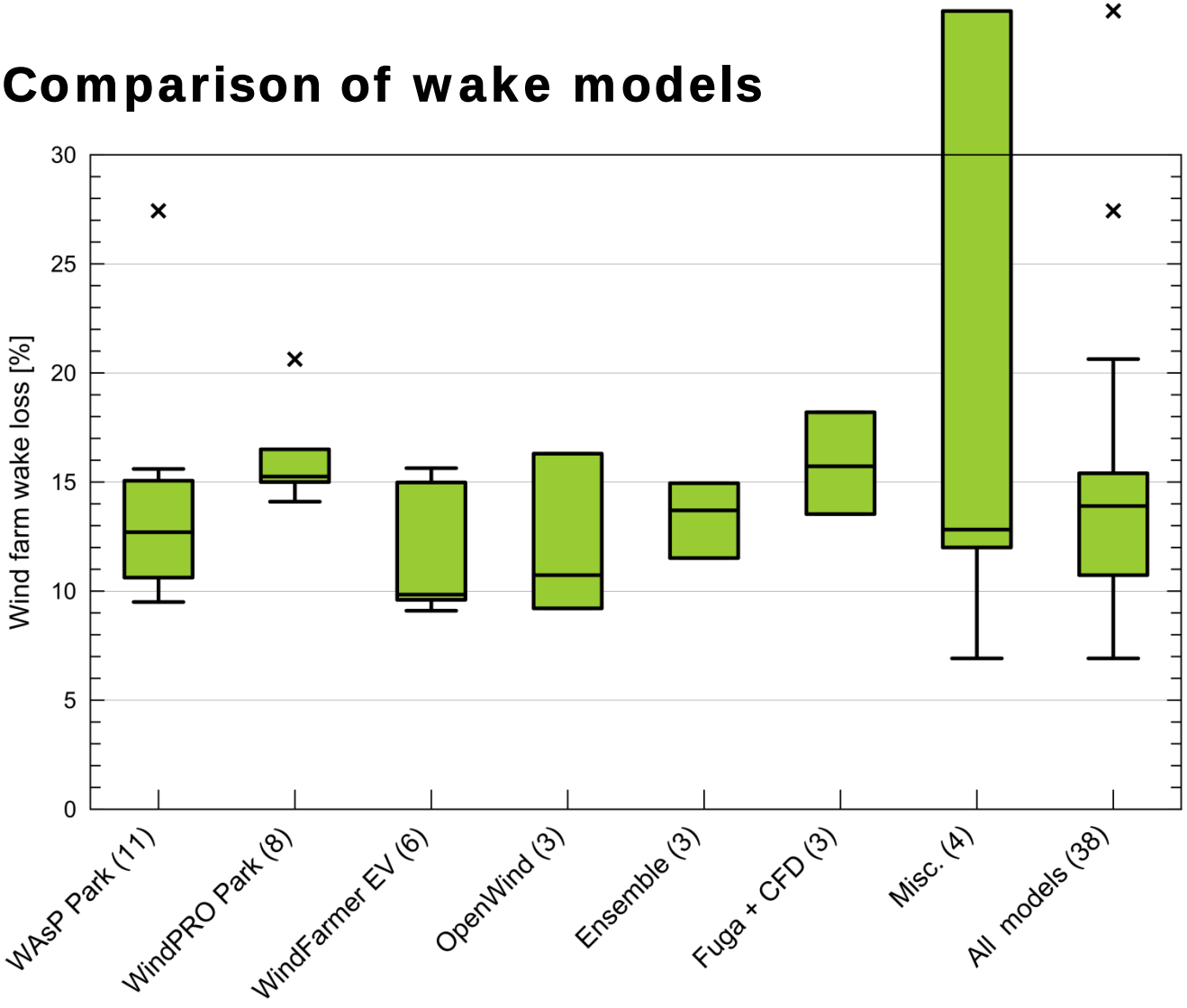
Standard deviation = 5.2%

Coefficient of variation = 37%

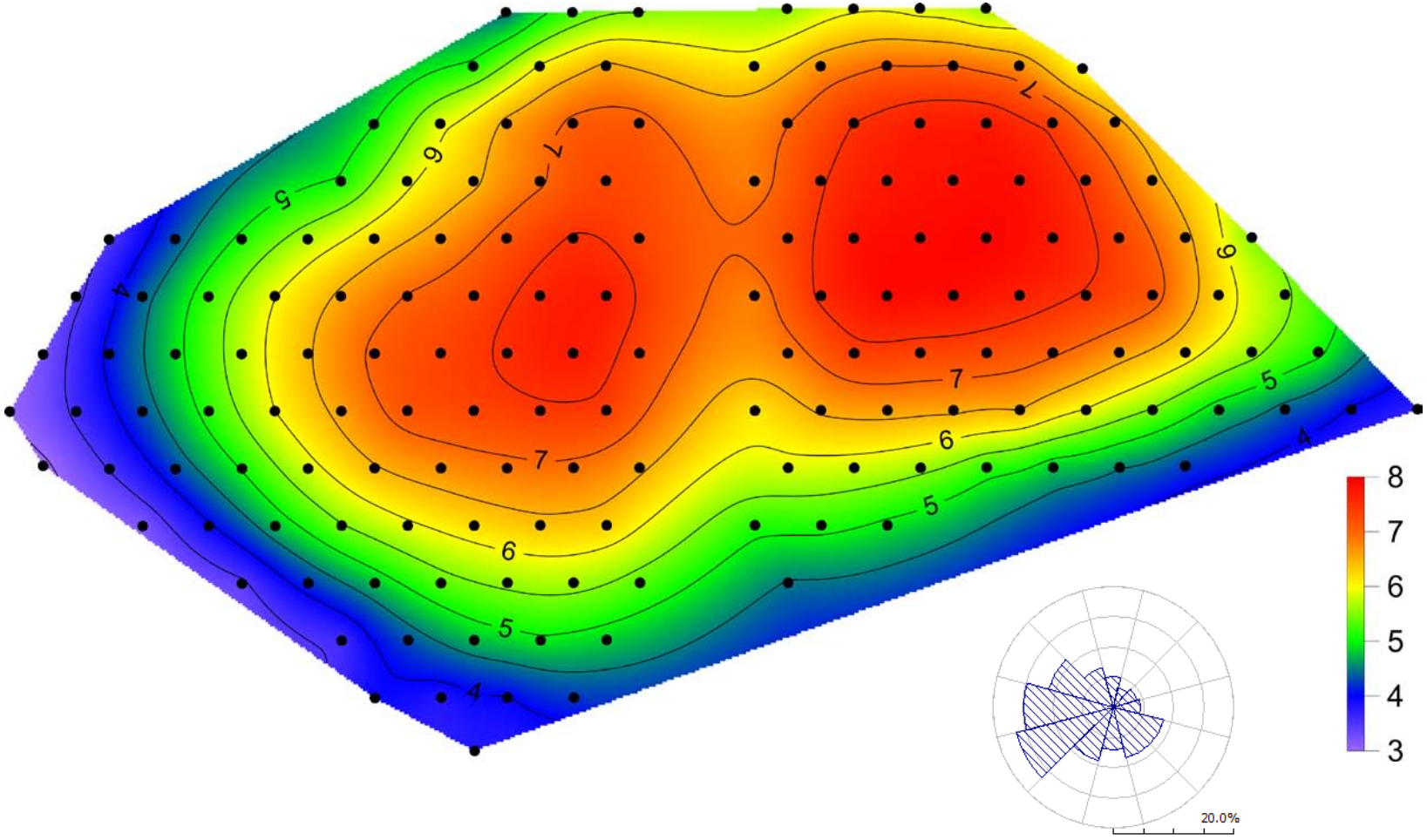
Range = 6.9% to 37%



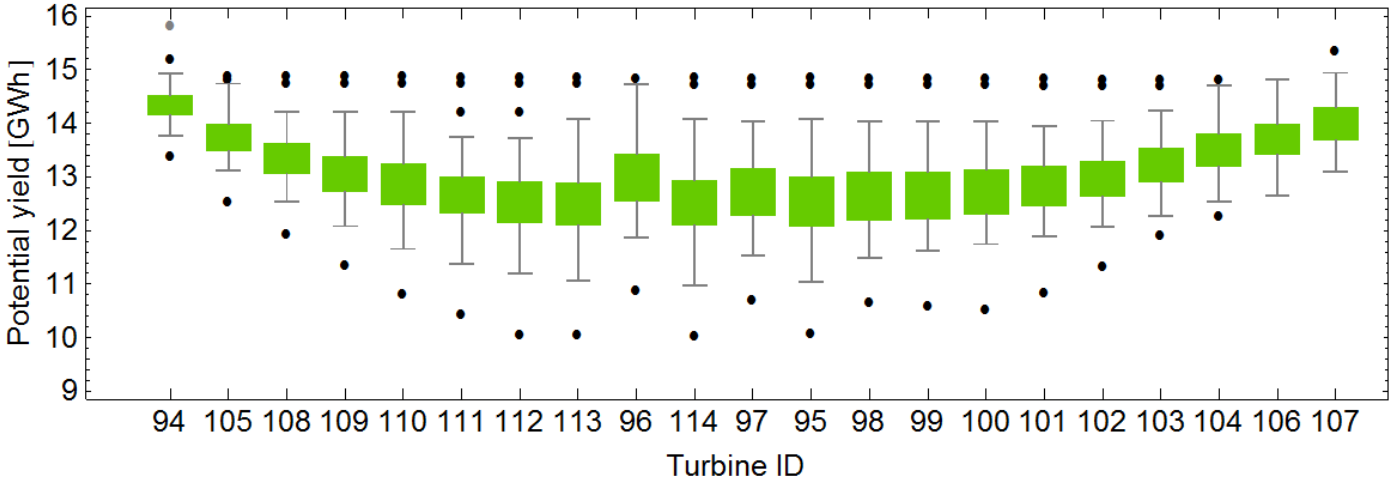
Comparison of wake models

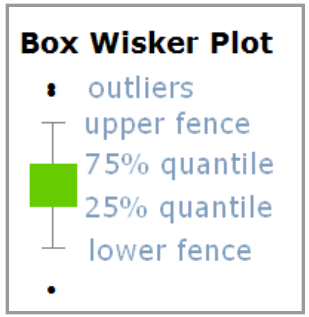


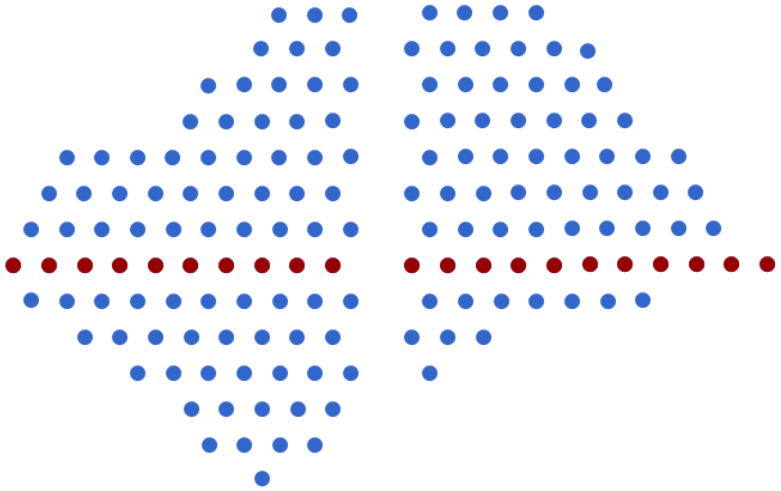
Turbine sites: coefficient of variation of AEP [%]



Statistics of predicted per-turbine energy yields





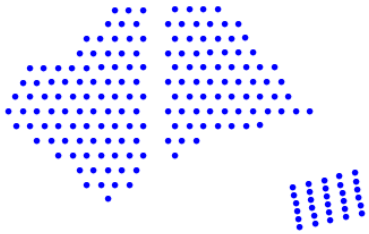


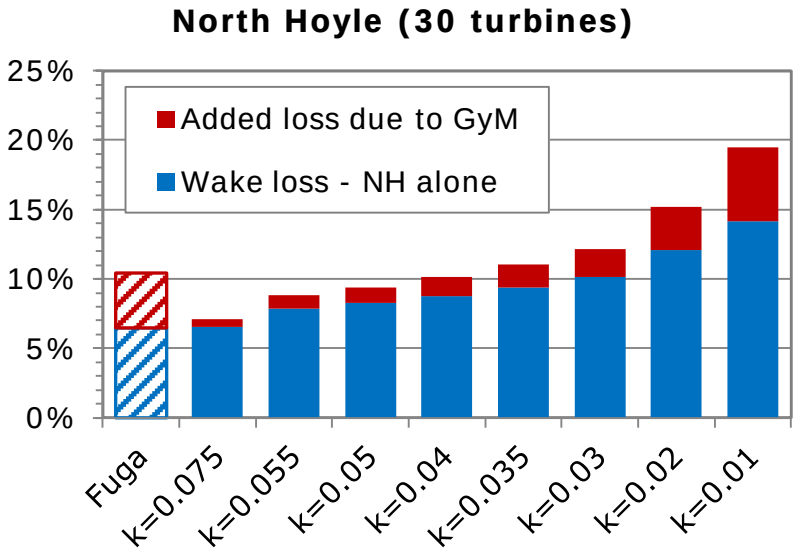
Effect of wake decay parameter *k* in PARK

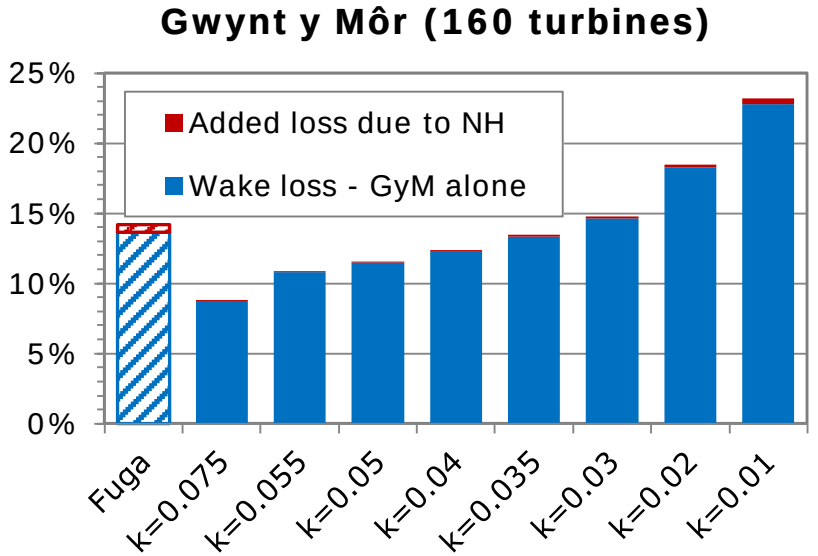
Comparison with Fuga (linearized CFD) suggests

- $k=0.03$ for wake effects at Gwynt y Môr (case study)
- $k=0.04$ for North Hoyle when including effect of Gwynt y Môr
- $k=0.075$ for North Hoyle before construction of Gwynt y Môr

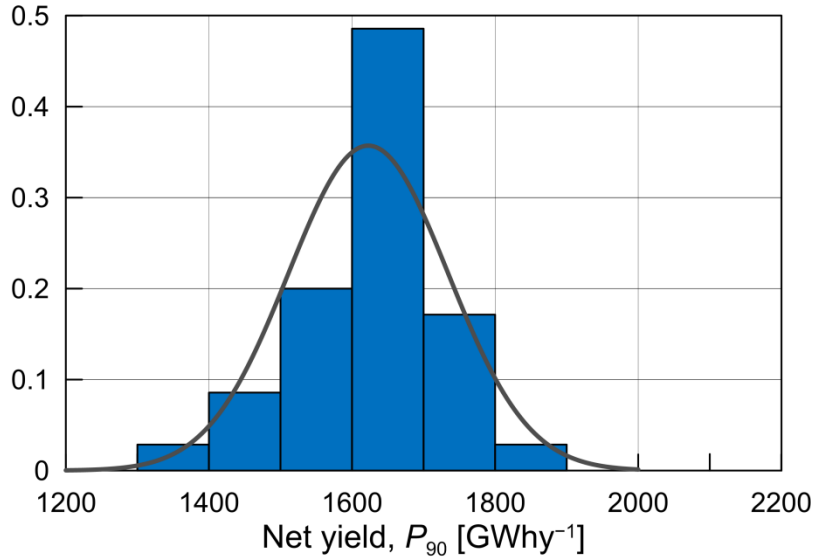
Probably no universal optimal offshore wake decay parameter!







Net energy yield of wind farm, P_{90}



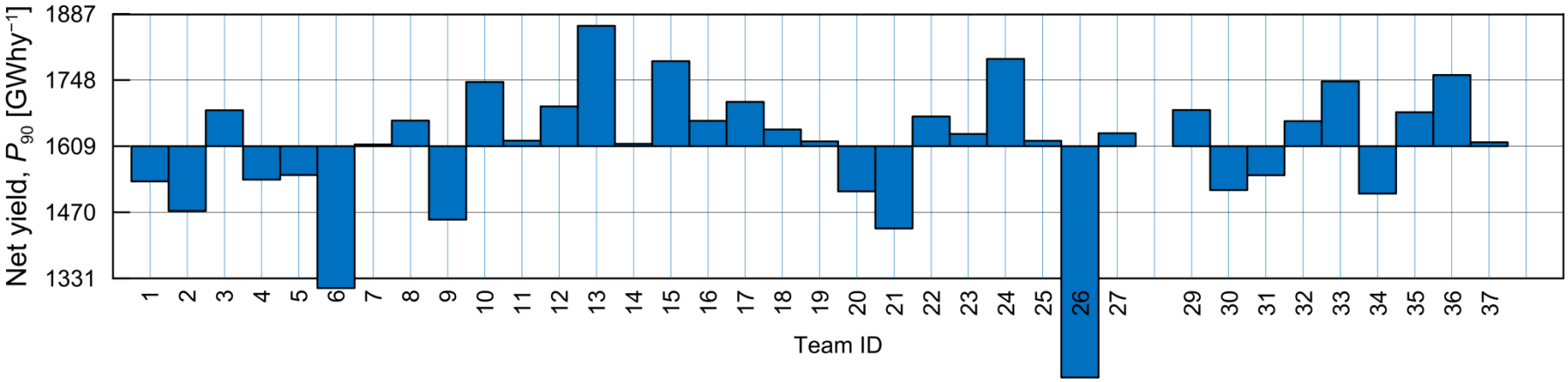
Data points used = 37 (of 38)

Mean net P_{90} yield = 1609 GWhy^{-1}

Standard deviation = 139 GWhy^{-1}

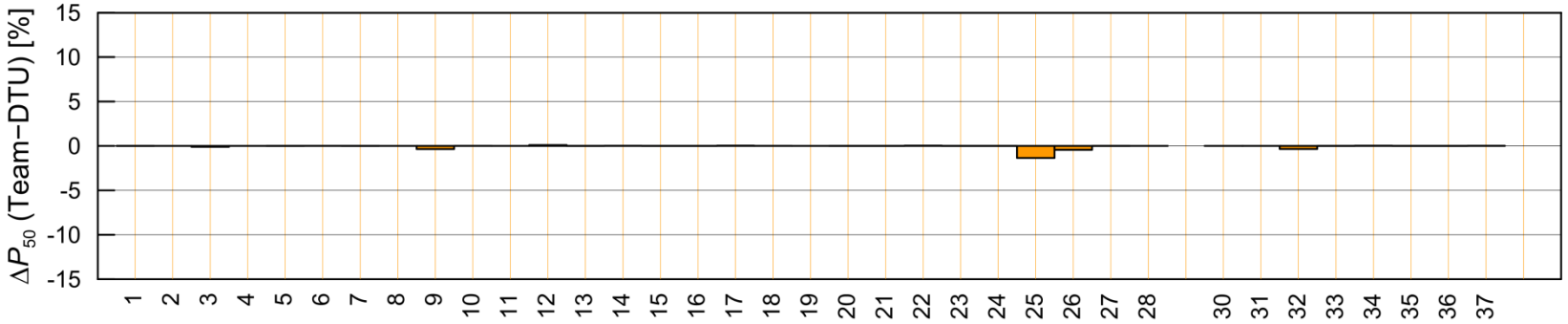
Coefficient of variation = 8.7%

Range = 1123 to 1862 GWhy^{-1}



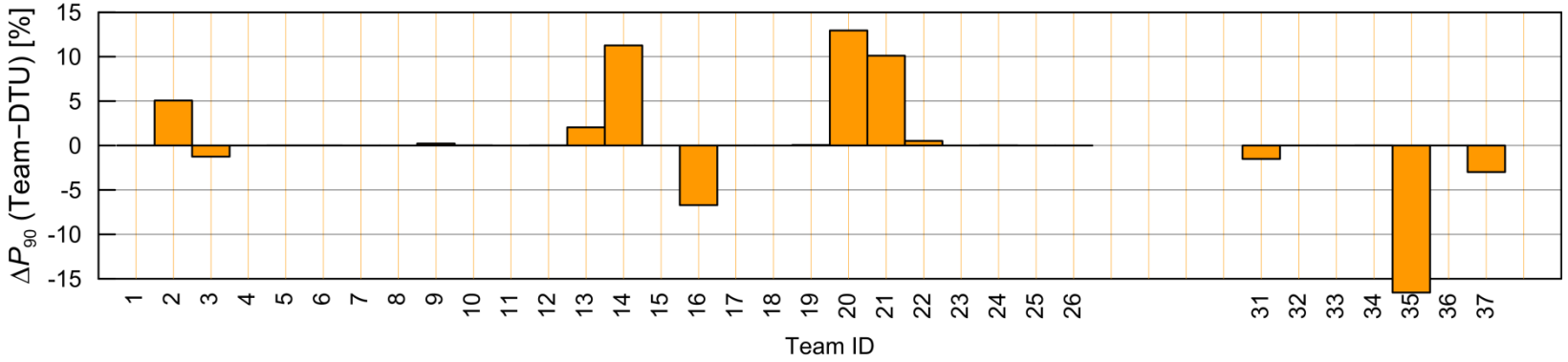
Quality assurance of submitted spreadsheets

Cross-check of P_{50}: team results compared to DTU calculation from team values.



- Net AEP (P_{90}) = Net AEP (P_{50}) − 1.282 × [uncertainty estimate]

Cross-check of P_{90}: ¾ of the teams agree with DTU, but ¼ get a different result!

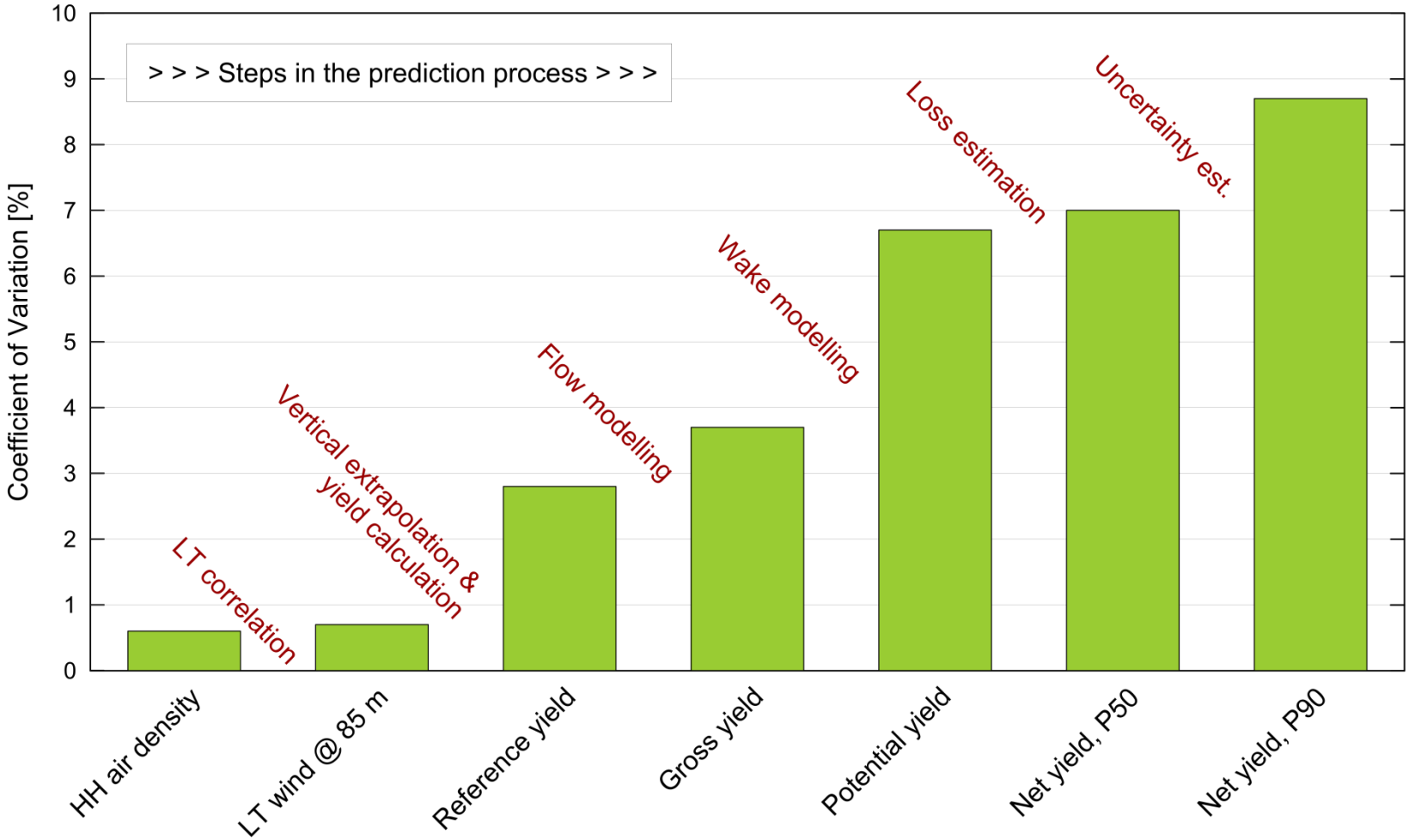


Wind farm key figures

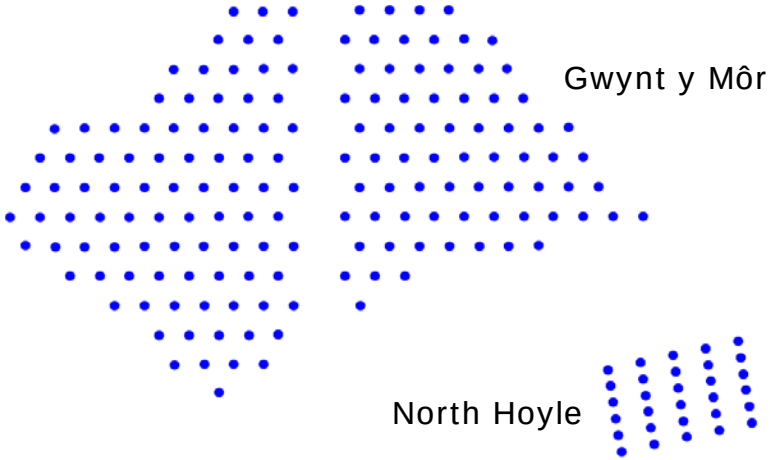
Gwynt y Môr		Mean	σ	CV*	Min	Max
Reference yield	GWh	2414	67	2.8	2287	2737
Topographic effects	%	n/a	n/a	n/a	n/a	n/a
Gross energy yield¶	GWh	2394	89	3.7	2178	2737
Wake loss	%	14	5.3	37	6.9	37
Potential yield	GWh	2052	138	6.7	1444	2251
Technical losses	%	9.6	0.7	7.8	7.5	13
Net energy yield P_{50}	GWh	1856	130	7.0	1296	2035
Uncertainty	%	10	3.1	29	6.2	21
Net energy yield P_{90}	GWh	1609	139	8.7	1123	1862

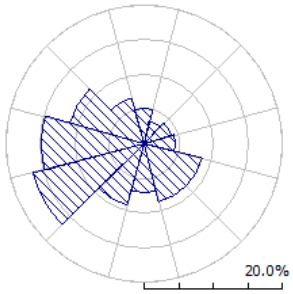
* Coefficient of Variation in per cent.
¶ Gross AEP inferred by DTU.

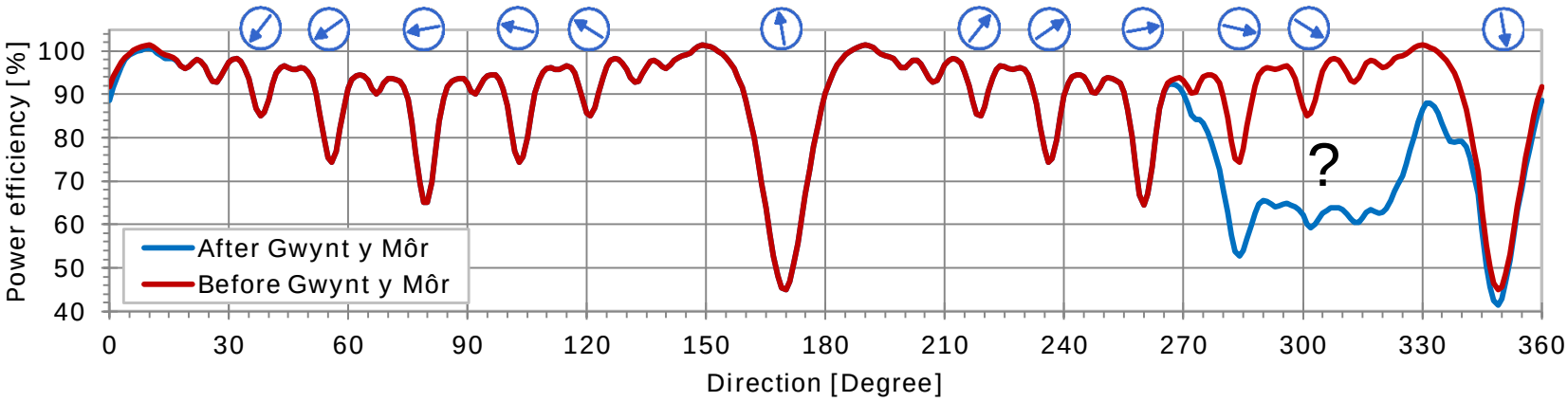
Spread for different steps in the prediction process



Wind farm efficiency of North Hoyle @ 10 ms^{-1}







Effect of Gwynt y Môr upon North Hoyle

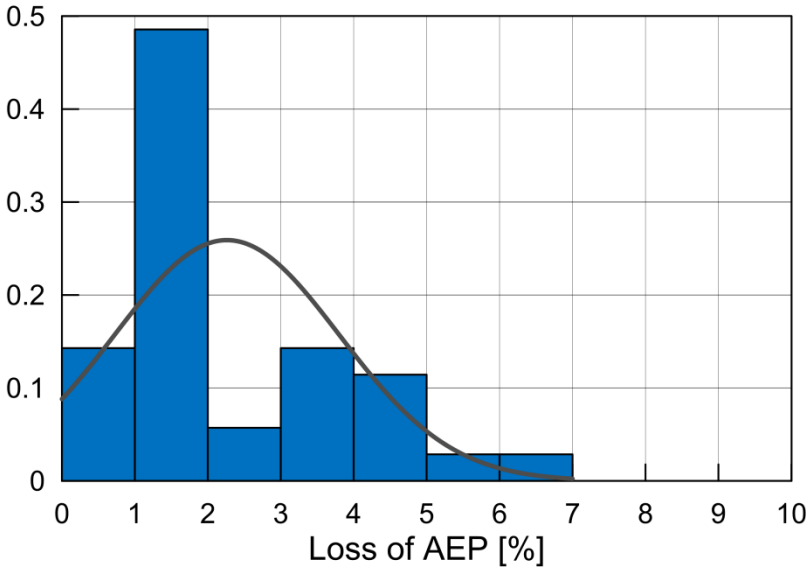
Data points used = 35 (of 38)

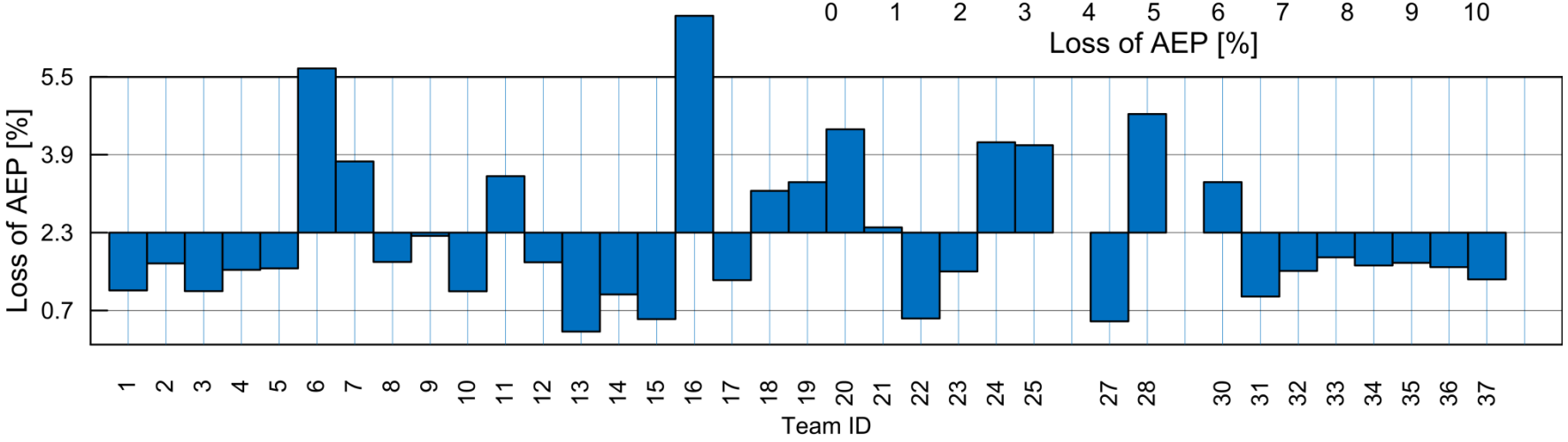
Mean loss of AEP = 2.3 %

Standard deviation = 1.6 %

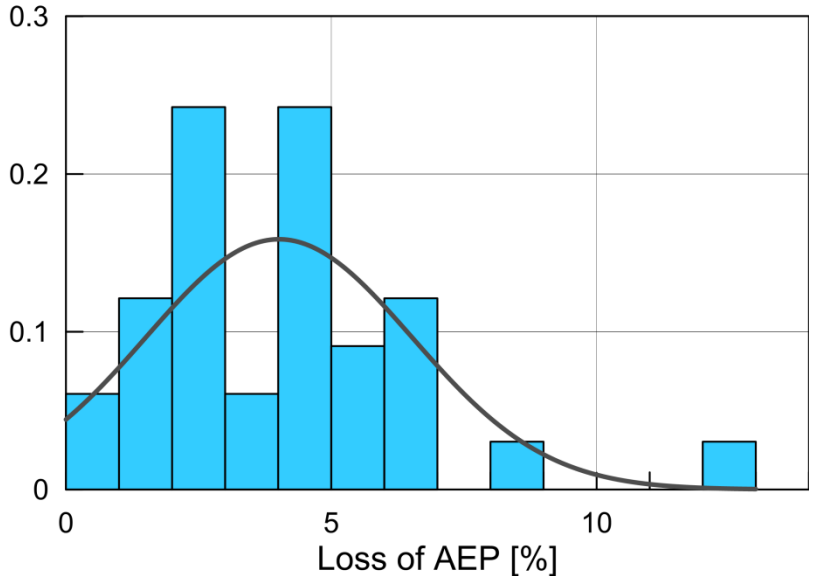
Coefficient of variation = 69%

Range = 0.3 to 6.8%





Loss due to 500-MW Export System Constraint



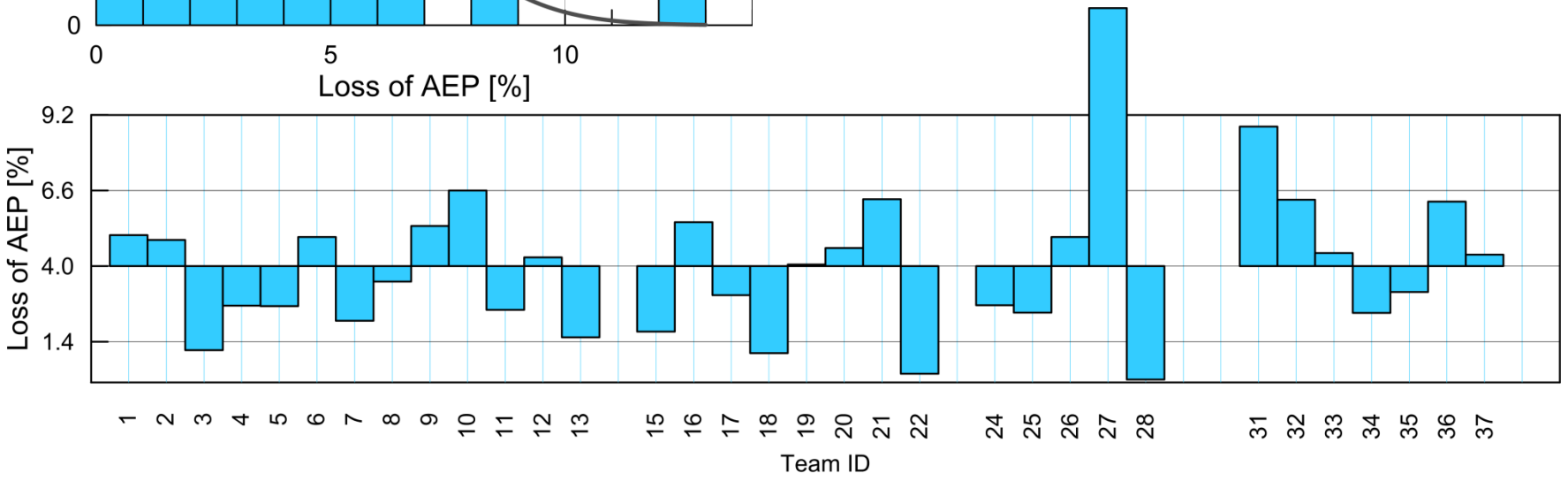
Data points used = 33 (of 38)

Mean loss of AEP = 4.0 %

Standard deviation = 2.6 %

Coefficient of variation = 64%

Range = 0.1 to 13%



Summary and conclusions

- Definition and usage of terms and concepts uncertain, e.g. *gross yield*
  - Adopt standards, guidelines, best practice (IEC, IEA, Measnet, ...)
  - Energy yield calculations must be unambiguous (P_{90}, loss factors, ...)
- Seemingly simple tasks introduce quite a bit of spread
  - Air density calculation, reference yield, long-term correlation, ...
- Wake modelling for Gwynt y Môr
  - Mean wake effect = 14.3%, standard deviation = 5.2% (CV = 37%)
  - Wake modelling uncertainty increases with depth into wind farm
- Overall spread of P_{90} predictions (~9%) quite similar to CREYAP I & II – and to the estimated uncertainty (~10%); but different steps may be different.
- Effect of Gwynt y Môr upon North Hoyle is clear, but a bit uncertain
  - Mean effect 2.3%, std. deviation 1.6% (CV = 69%), 0.3 to 6.8%
- Loss due to 500-MW Export System Constraint is clear, but a bit uncertain
  - Mean effect 4.0%, std. deviation 2.6% (CV = 64%), 0.1 to 13%


Thank you for your attention!

Appendices

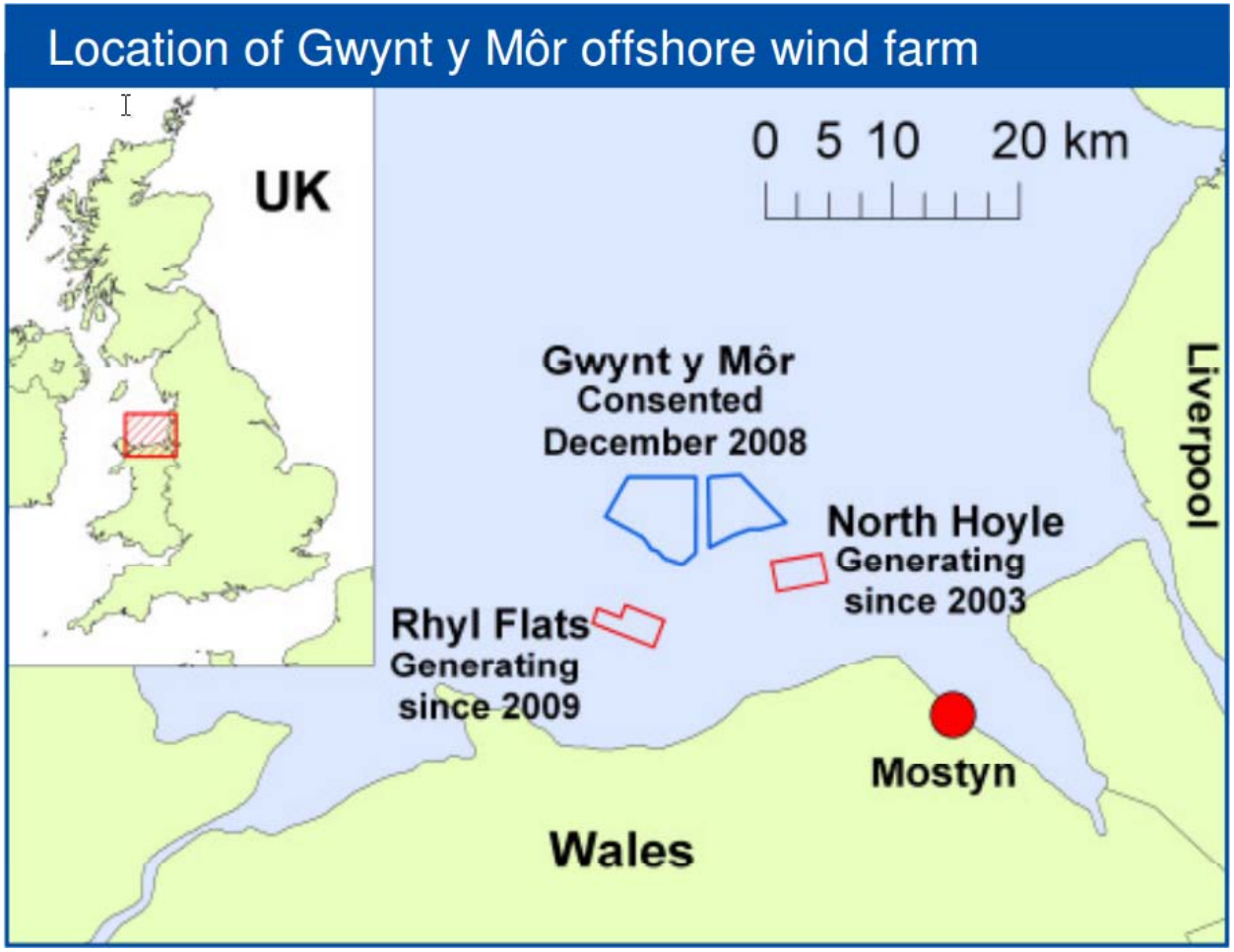
Team results, statistics and additional information ↑

Who submitted results?

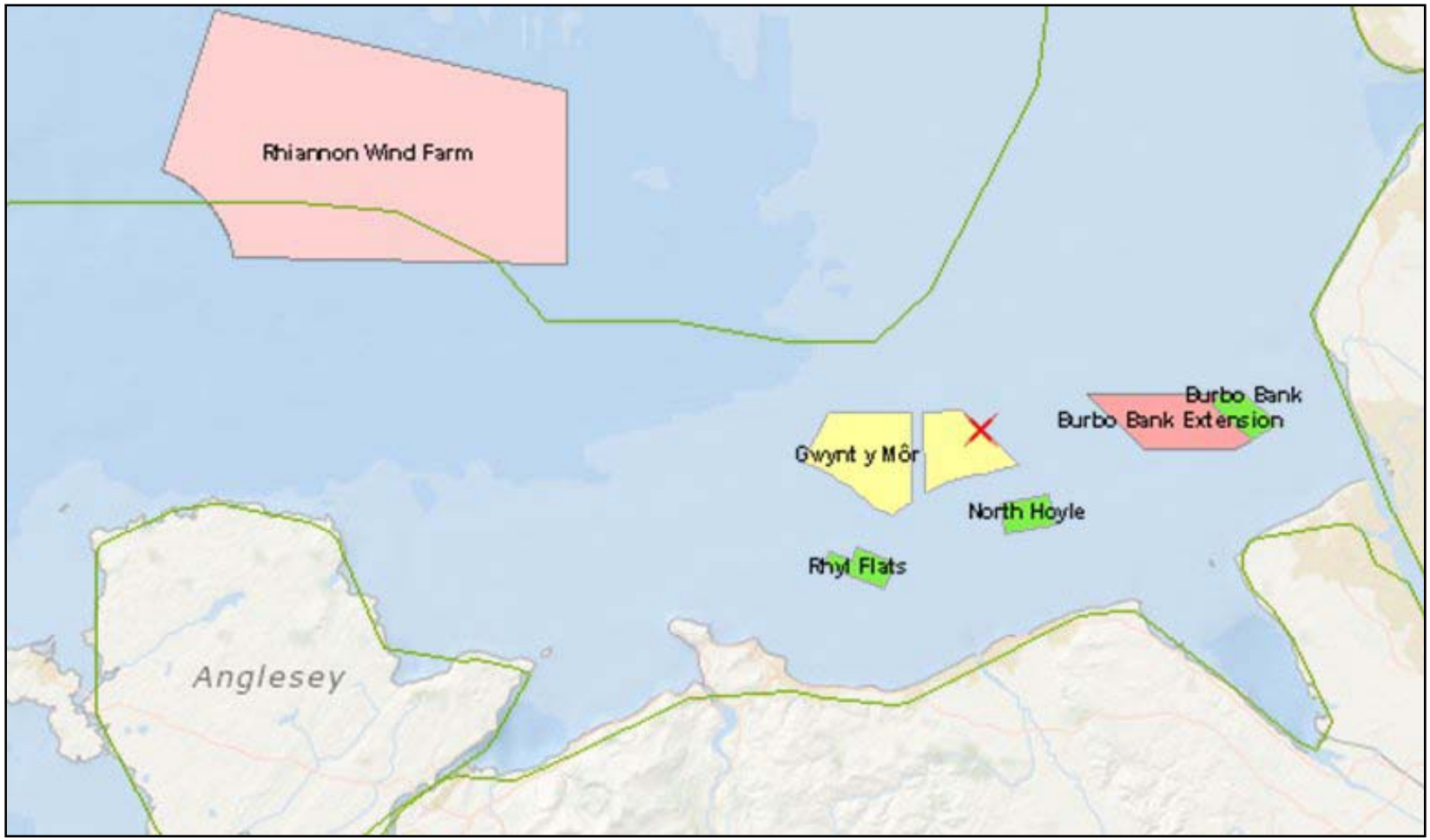
- 37 organisations (38 teams) from 13 countries submitted results
  - Belgium, China, Denmark, Finland, Germany, India, Italy, Japan, Norway, Poland, Spain, United Kingdom, USA

- Names of organisations
  - 3E, AWS Truepower, Barlovento Recursos Naturales, CENER, CIRCE – Research Center for Energy Resources and Consumption, DONG Energy Wind Power, DTU Wind Energy, EMD International, Enerpark Inzynieria Wiatrowa, EREDA SLU, Etha Ab, Fraunhofer IWES, Fujian Hydro Power, Gamesa Corporación Tecnológica, GL Garrad Hassan, Grupo COBRA (EYRA), Ingham Consult ApS, Lahmeyer International GmbH, Mott MacDonald, Mytrah Energy (India) Ltd, Natural Power, Prevailing Ltd, REpower Systems, RES Group, RSE S.p.A., Statoil, The Wind Consultancy Service, Tractebel Engineering, Vattenfall, Wind Energy Corporation, Wind Prospect Group Limited, WIND-consult GmbH, WindGuard, WindSim AS, Winwind Ltd, YCON BVBA

Gwynt y Môr wind farm setting



Gwynt y Môr wind farm setting



Comparisons of results and methods {definitions}

1. LT wind @ 85 m (mast) = Measured wind ± [long-term adjustment]
   - comparison of long-term adjustment methods
2. LT wind @ 79 m (hub height)= LT wind @ 85 m + [wind profile effects]
   - comparison of vertical extrapolation methods
3. Gross AEP = Reference AEP ± [terrain effects]
   - comparison of flow models
4. Potential AEP = Gross AEP – [wake losses]
   - comparison of wake models
5. Net AEP (P_{50}) = Potential AEP – [technical losses]
   - comparison of technical losses estimates
6. Net AEP (P_{90}) = Net AEP (P_{50}) – 1.282 × [uncertainty estimate]
   - comparison of uncertainty estimates
7. Comparison to teams average AEP – spread and bias

Comparisons of results and methods {notes}

- Comparison of long-term correlation methods
  - MCP using site and MERRA data, no adjustment factors given by teams
- Comparison of vertical extrapolation methods
  - Wind shear exponent of 0.1 prescribed, no shear factors given by teams
- Comparison of flow models
  - Terrain effects not given by teams
- Comparison of wake models
  - Illustrated in presentation in several ways
- Comparison of technical losses estimates
  - Losses prescribed, except hysteresis effect which is illustrated below
- Comparison of uncertainty estimates
  - Uncertainty components are participants own choice; it has not been possible to brake this down for the presentation.

Long-term wind speed @ 85 m

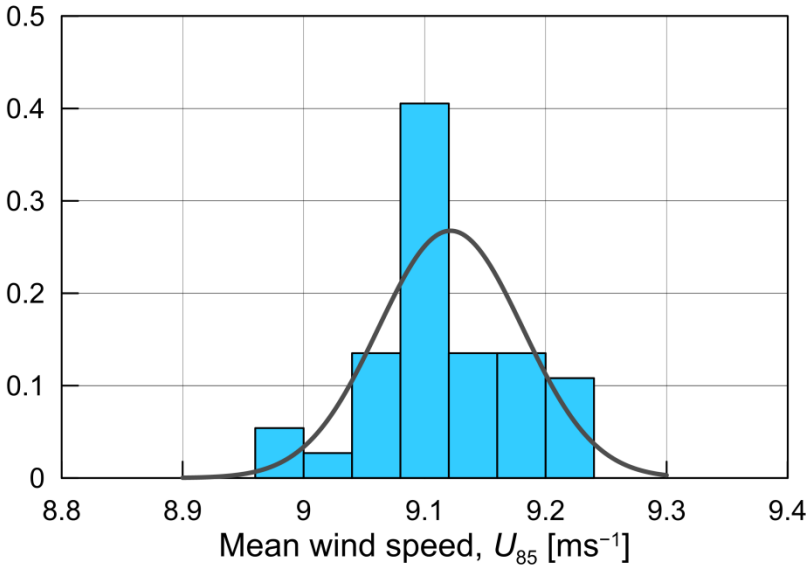
Data points used = 37 (of 38)

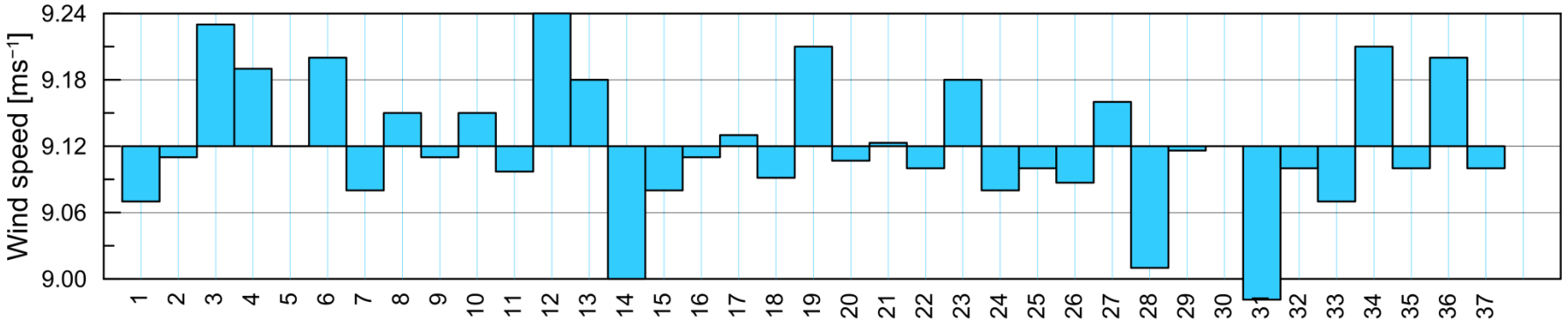
Mean wind speed = 9.12 ms^{-1}

Standard deviation = 0.06 ms^{-1}

Coefficient of variation = 0.7%

Range = 8.98 to 9.24 ms^{-1}





Wind speed uncertainty @ 85 m

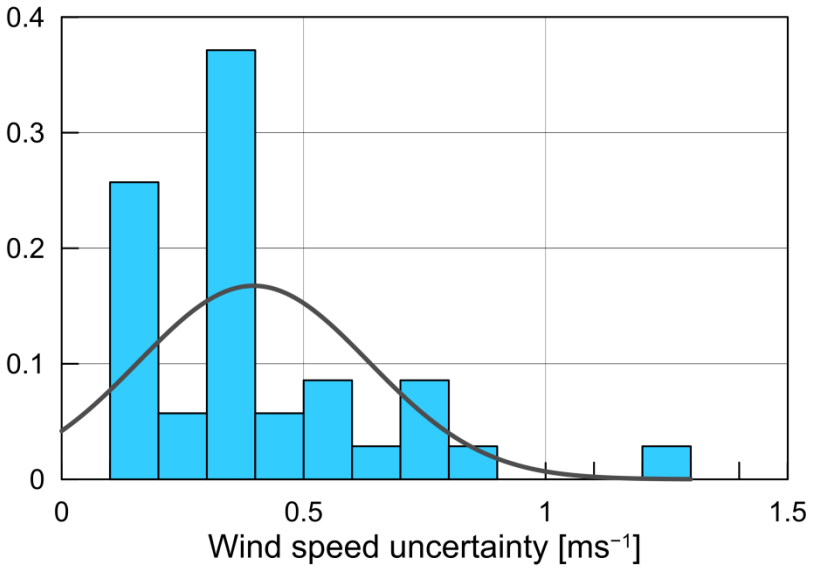
Data points used = 37 (of 38)

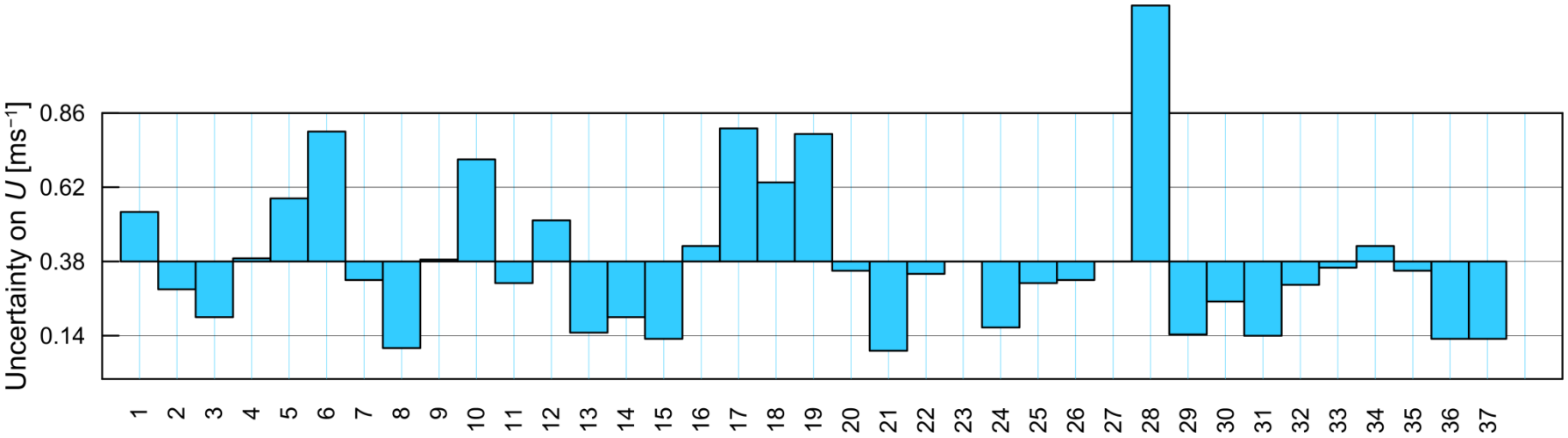
Mean uncertainty = 0.38 ms^{-1}

Standard deviation = 0.24 ms^{-1}

Coefficient of variation = 64%

Range = 0.09 to 1.21 ms^{-1}





Turbulence intensity @ 85 m

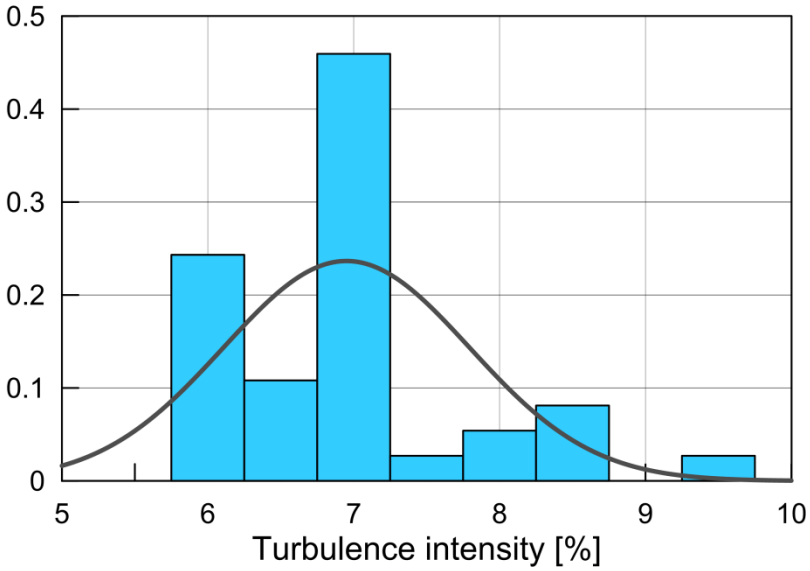
Data points used = 37 (of 38)

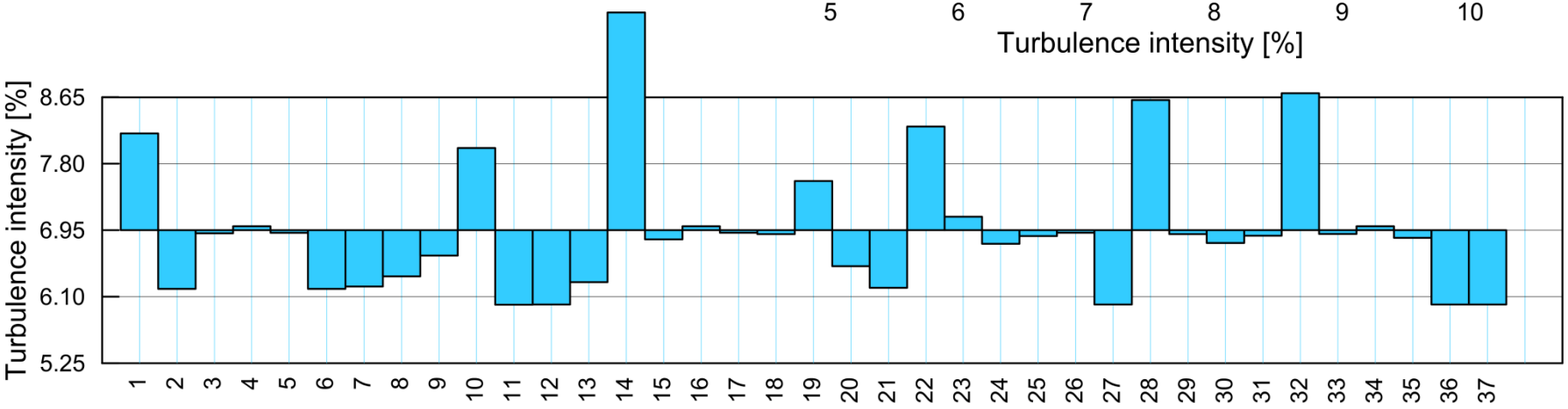
Mean turbulence intensity = 7.0%

Standard deviation = 0.9%

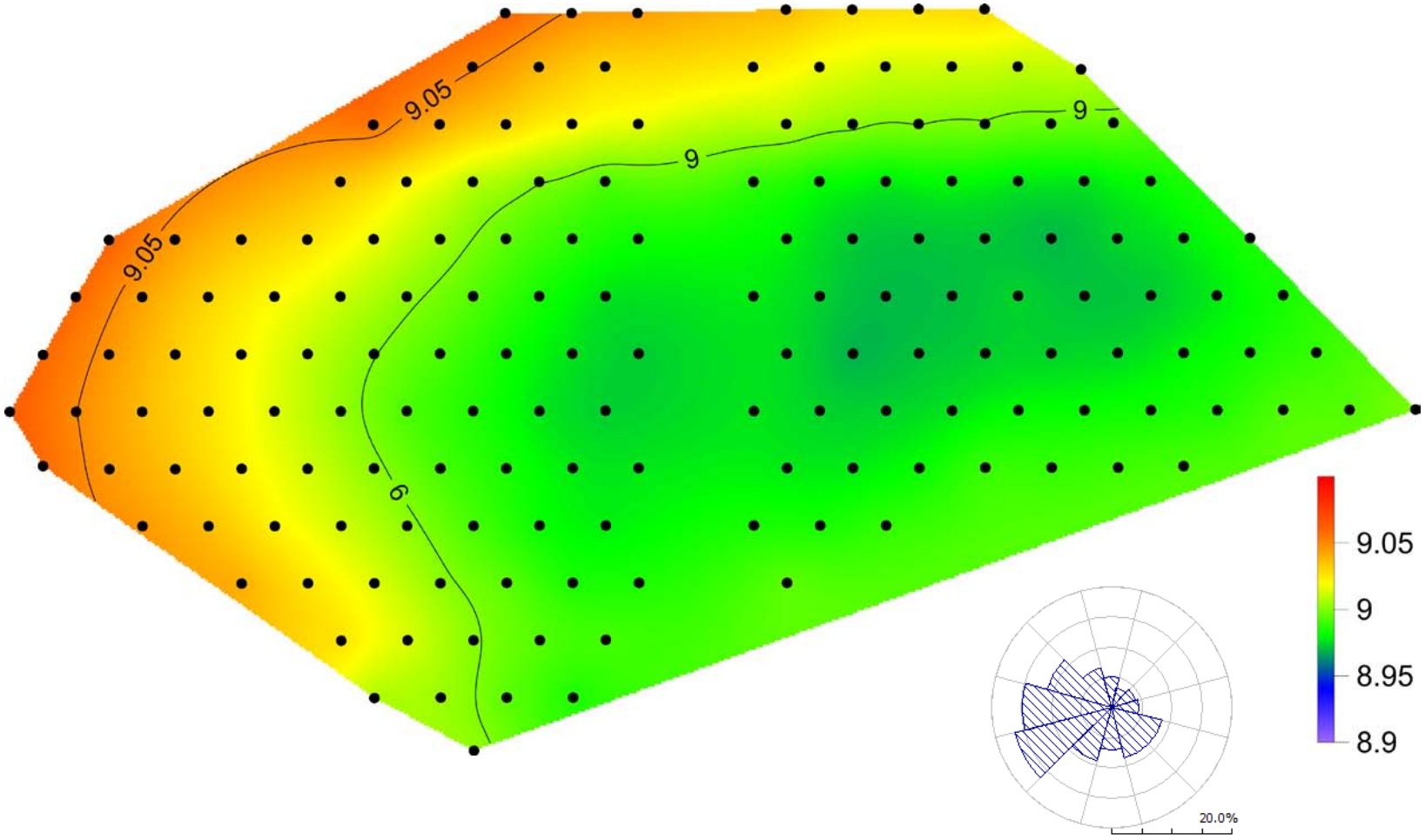
Coefficient of variation = 12.3%

Range = 6.0 to 9.7%

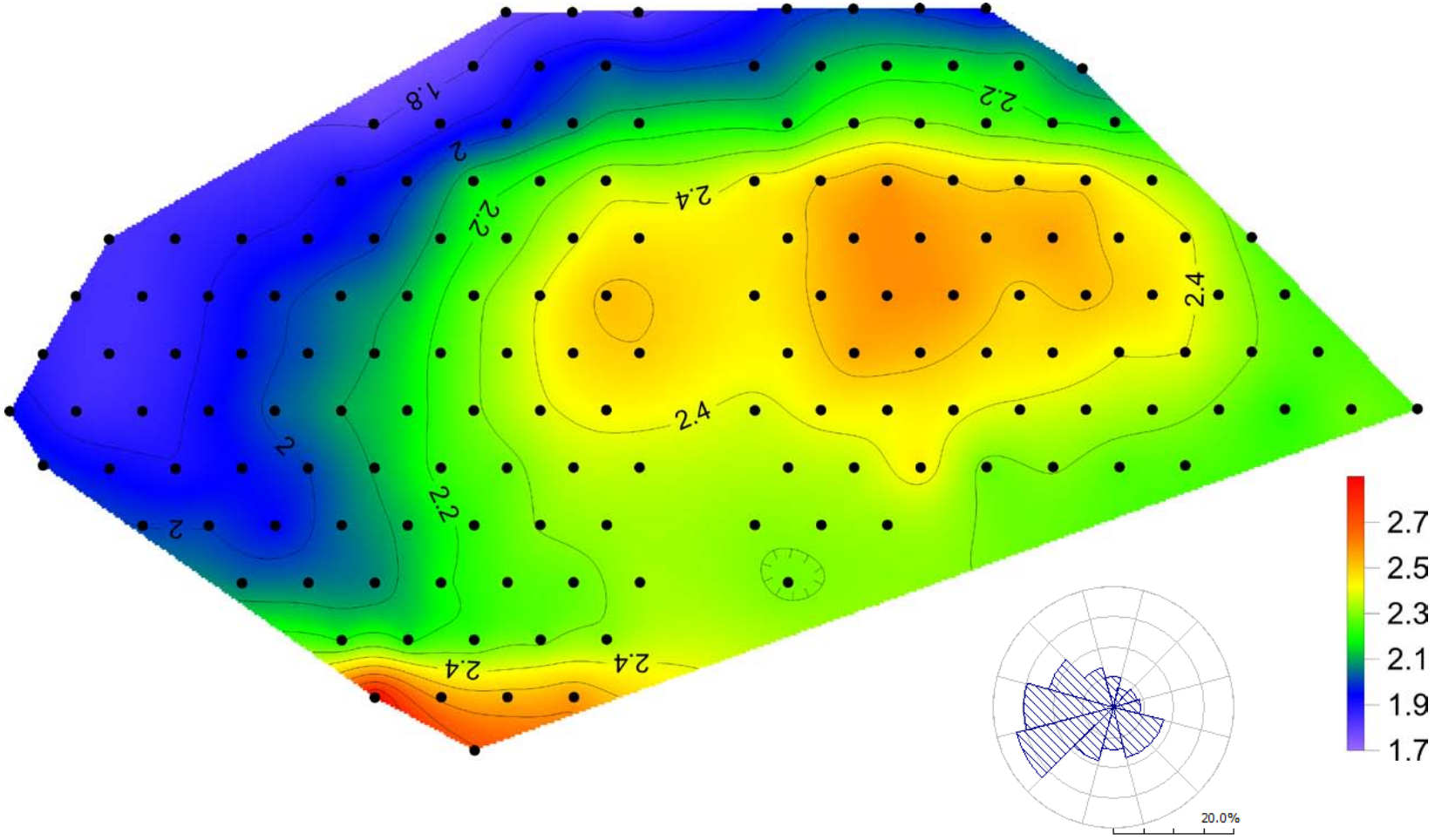




Turbine site mean wind speed [ms^{-1}]



Turbine site wind speed CV [%]



Mean air density @ 20 m

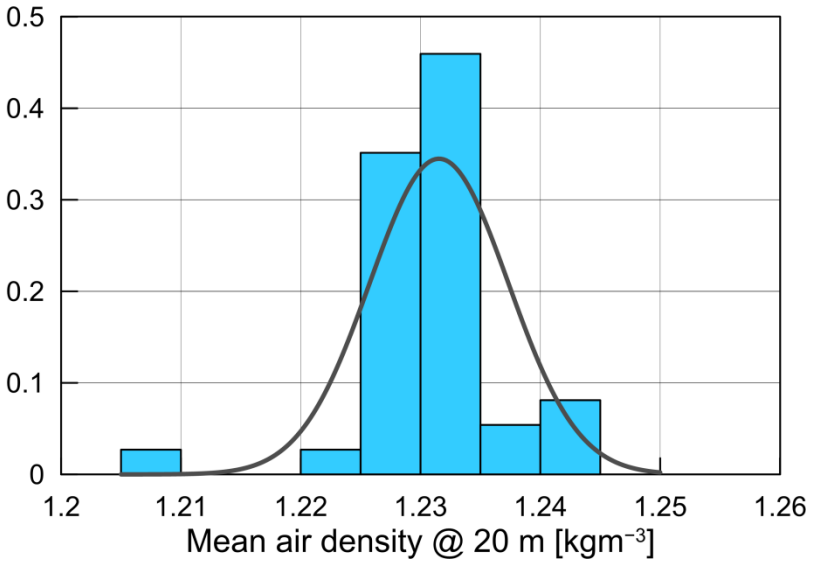
Data points used = 37 (of 38)

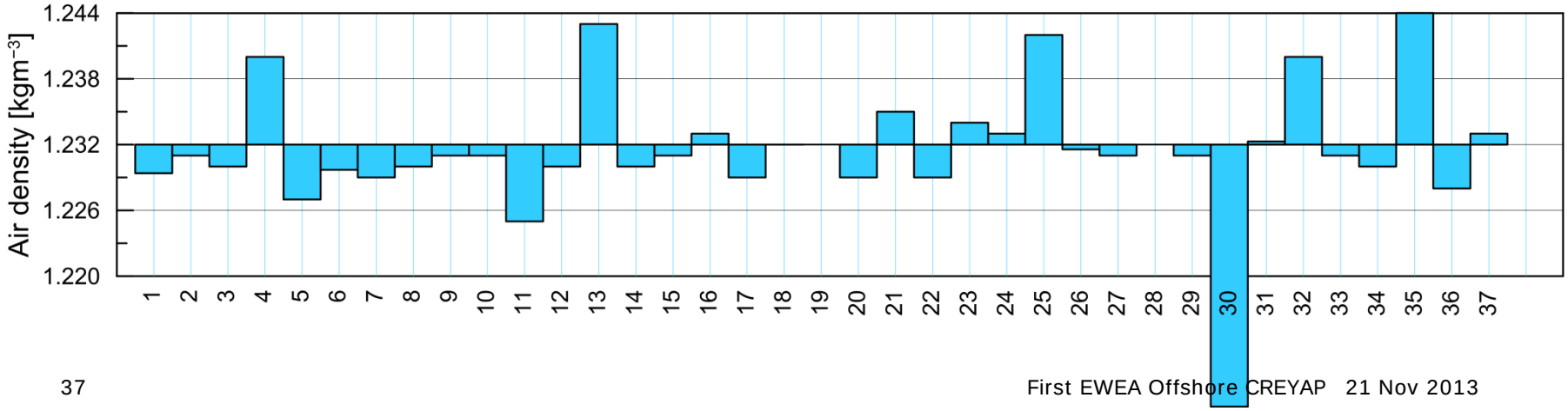
Mean air density = 1.232 kgm^{-3}

Standard deviation = 0.006 kgm^{-3}

Coefficient of variation = 0.5%

Range = 1.208 to 1.244 kgm^{-3}





Mean air density ρ @ hub height

Data points used = 36 (of 38)

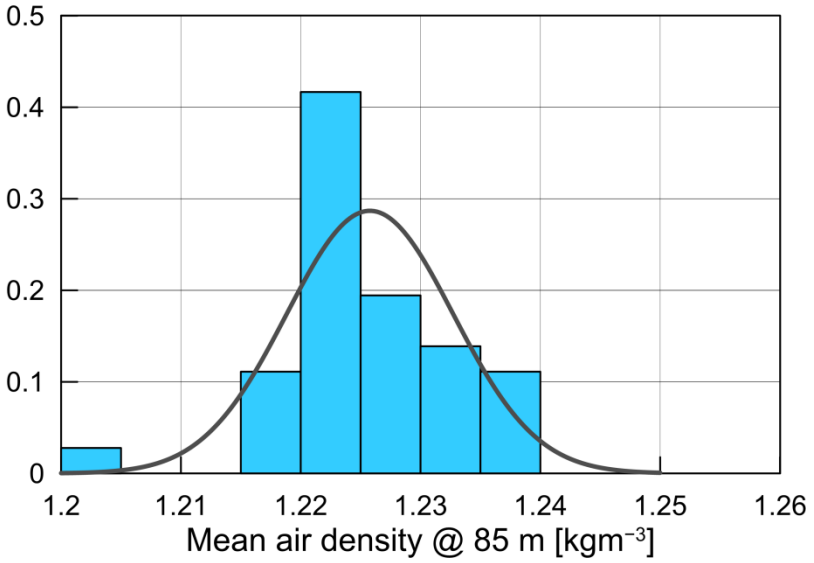
Mean air density = 1.226 kgm^{-3}

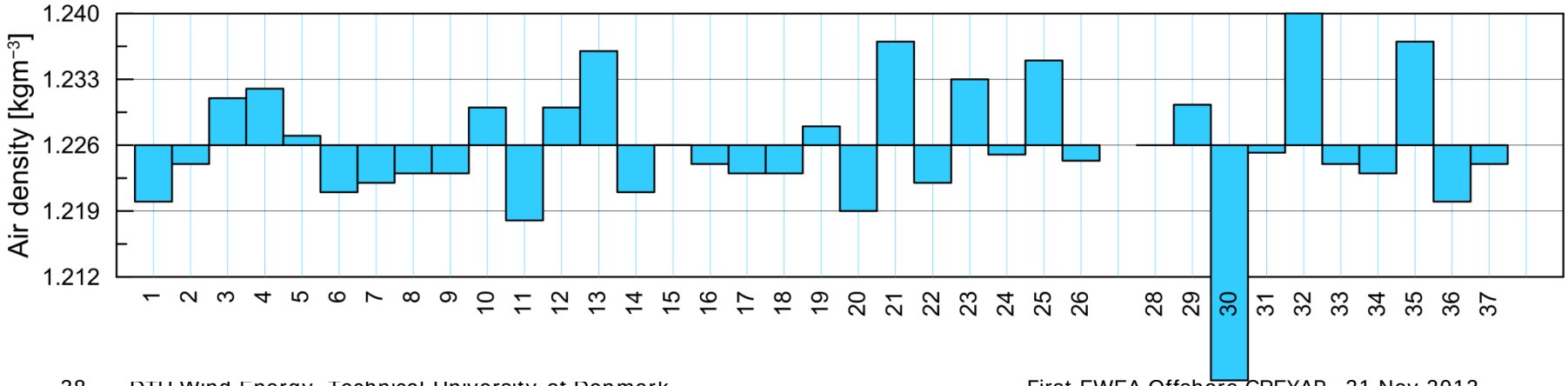
Standard deviation = 0.007 kgm^{-3}

Coefficient of variation = 0.6%

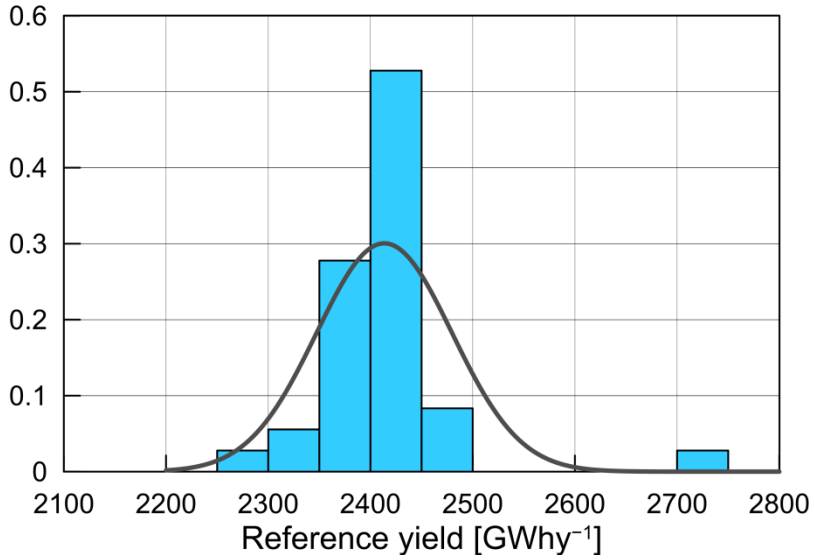
Range = 1.201 to 1.240 kgm^{-3} (3%)

AEP sensitivity ~ 0.5% for 1% in ρ





Reference yield



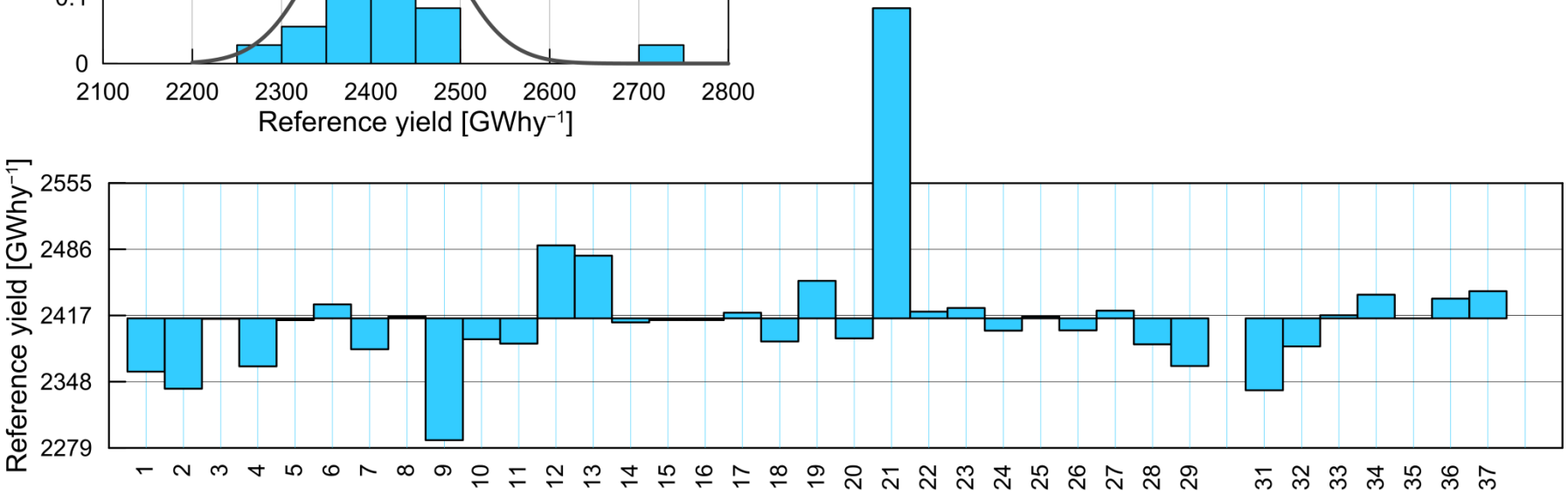
Data points used = 36 (of 38)

Mean reference yield = 2414 $GWhy^{-1}$

Standard deviation = 67 $GWhy^{-1}$

Coefficient of variation = 2.8%

Range = 2287 to 2737 $GWhy^{-1}$

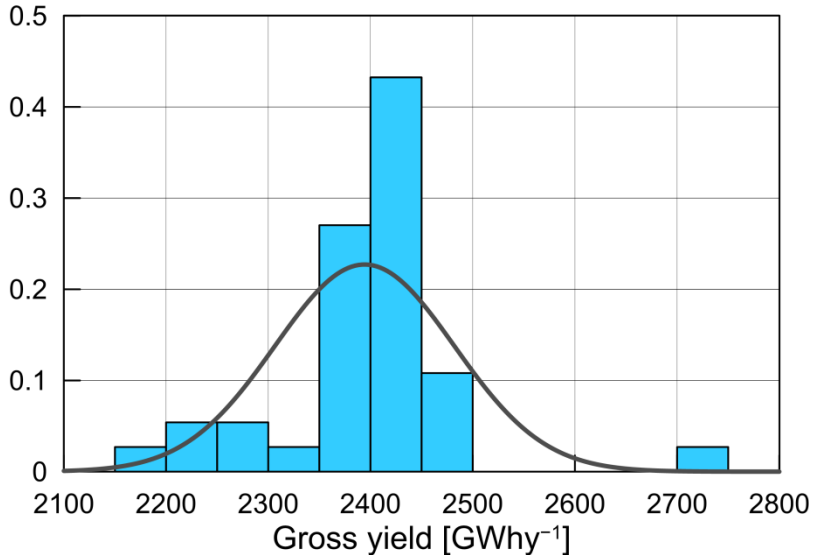


Comparison of flow models

It is not straightforward to compare the horizontal extrapolation methods quantitatively, but here is a list of the methods specified by the teams:

- WAsP – 24 teams, 2 through WindPRO interface
- WRF – 3 teams, 1 together with GLGH VMD
- Vortex – 2 teams
- Mesoscale – 2 teams, unspecified model
- SiteWind – 2 teams
- OpenWind – 1 team
- WindSim – 1 team
- CFD – 1 team, unspecified model
- Skiron – 1 team, mesoscale model
- Not available – 1 team

Gross yield



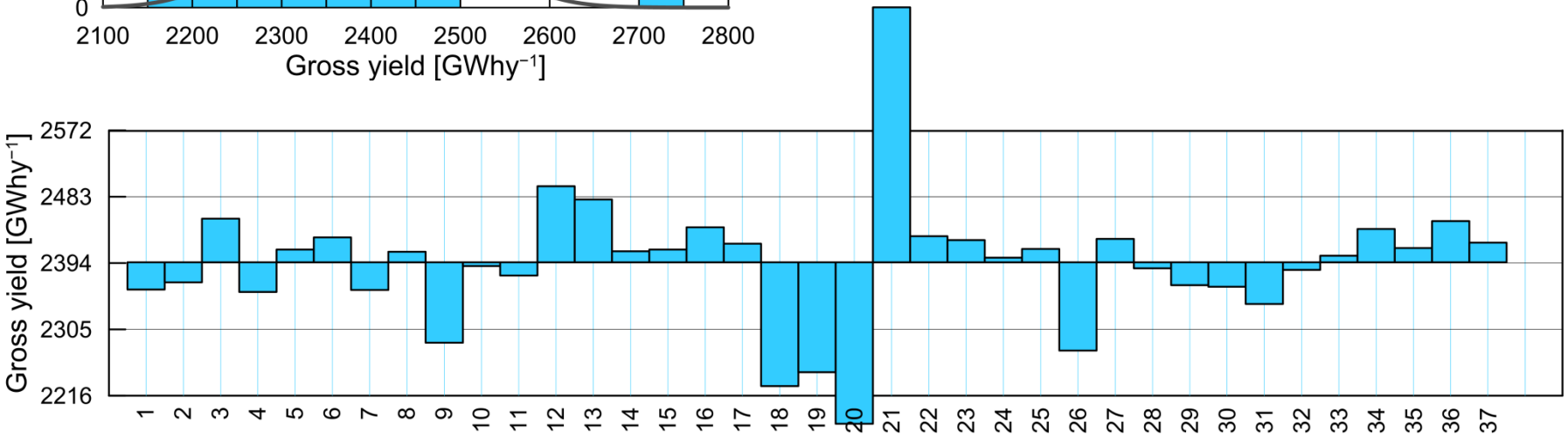
Data points used = 37 (of 38)

Mean reference yield = 2394 $GWhy^{-1}$

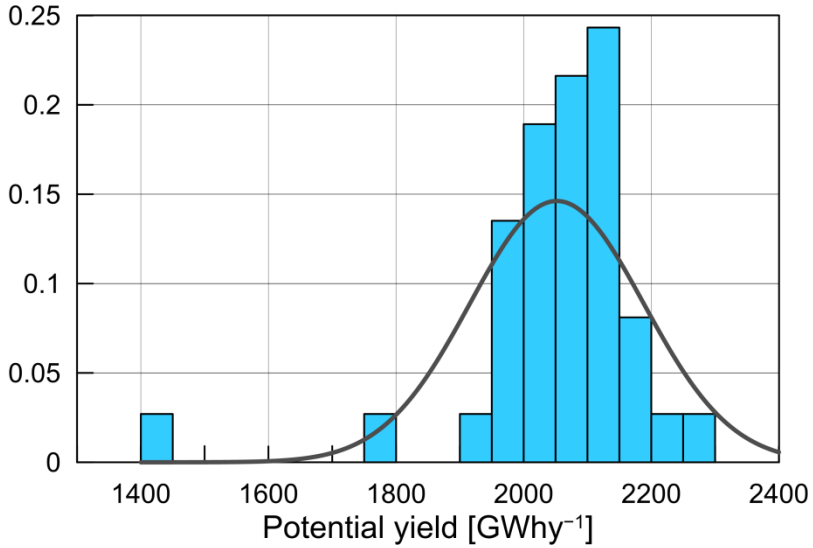
Standard deviation = 89 $GWhy^{-1}$

Coefficient of variation = 3.7%

Range = 2178 to 2737 $GWhy^{-1}$



Potential yield



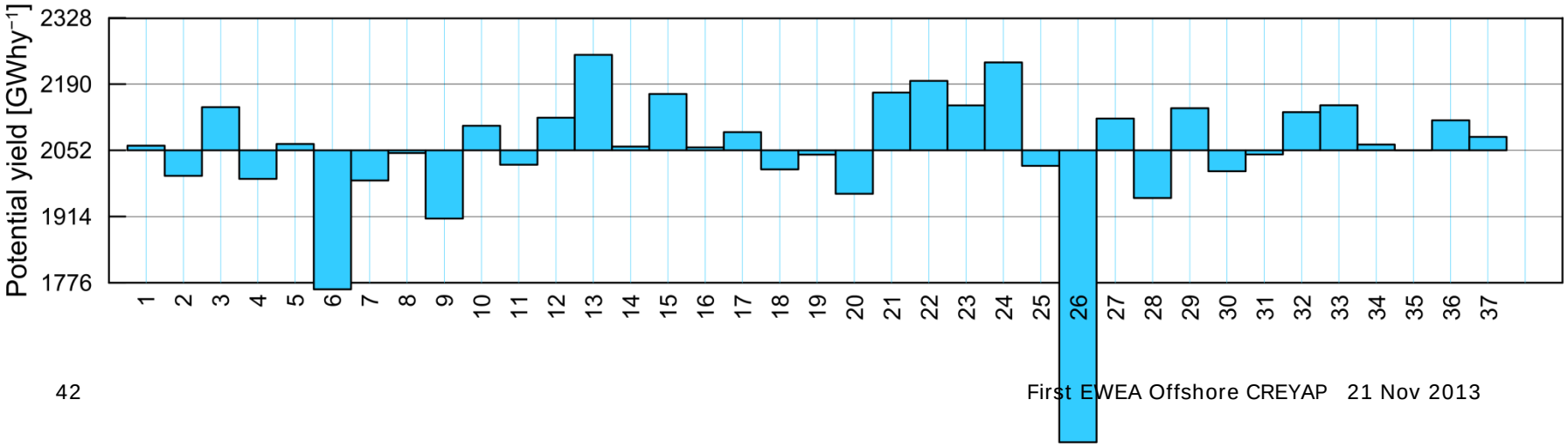
Data points used = 36 (of 38)

Mean potential yield = 2052 $GWhy^{-1}$

Standard deviation = 138 $GWhy^{-1}$

Coefficient of variation = 6.7%

Range = 1444 to 2251 $GWhy^{-1}$



Technical losses

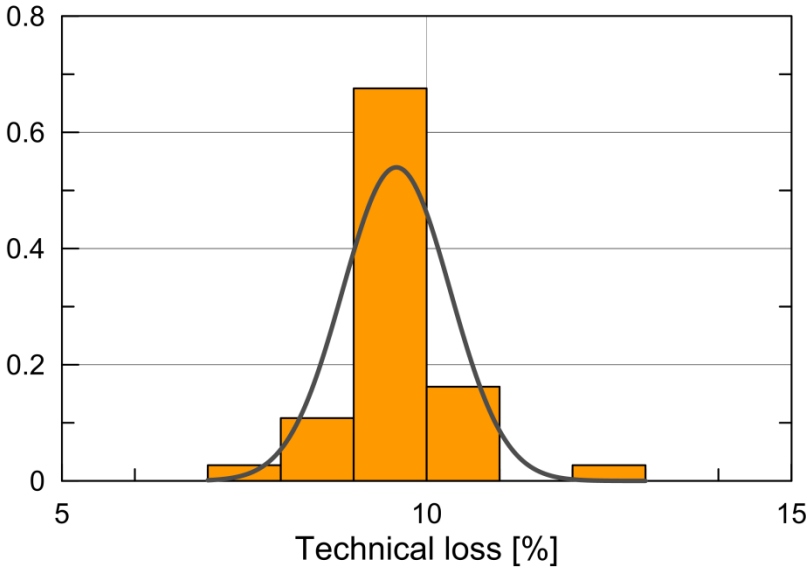
Data points used = 37 (of 38)

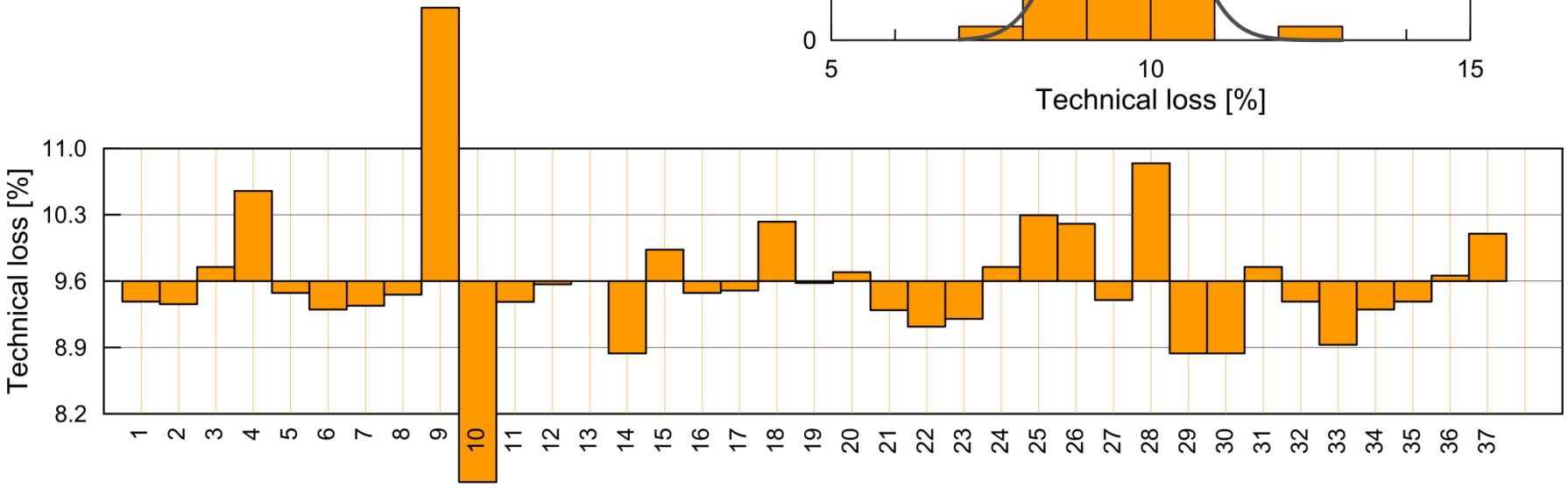
Mean technical loss = 9.6%

Standard deviation = 0.7%

Coefficient of variation = 7.8%

Range = 7.5 to 13%





Hysteresis effect factor

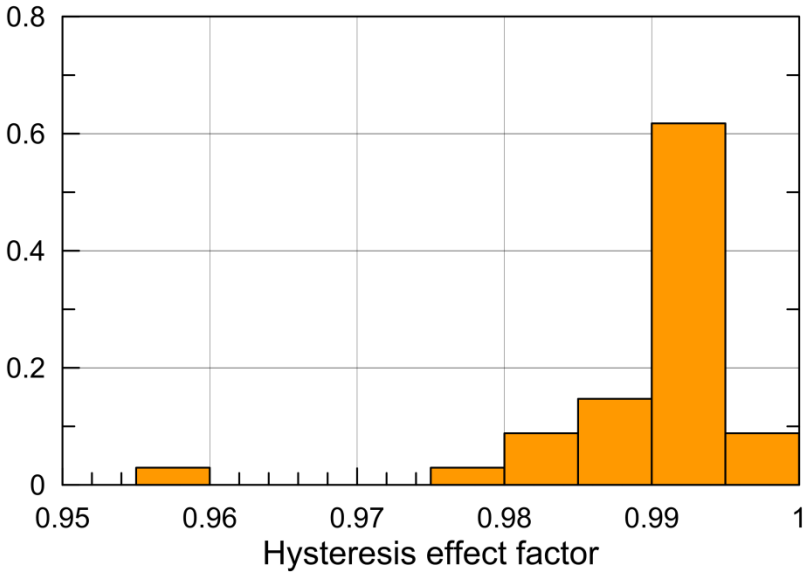
Data points used = 37 (of 38)

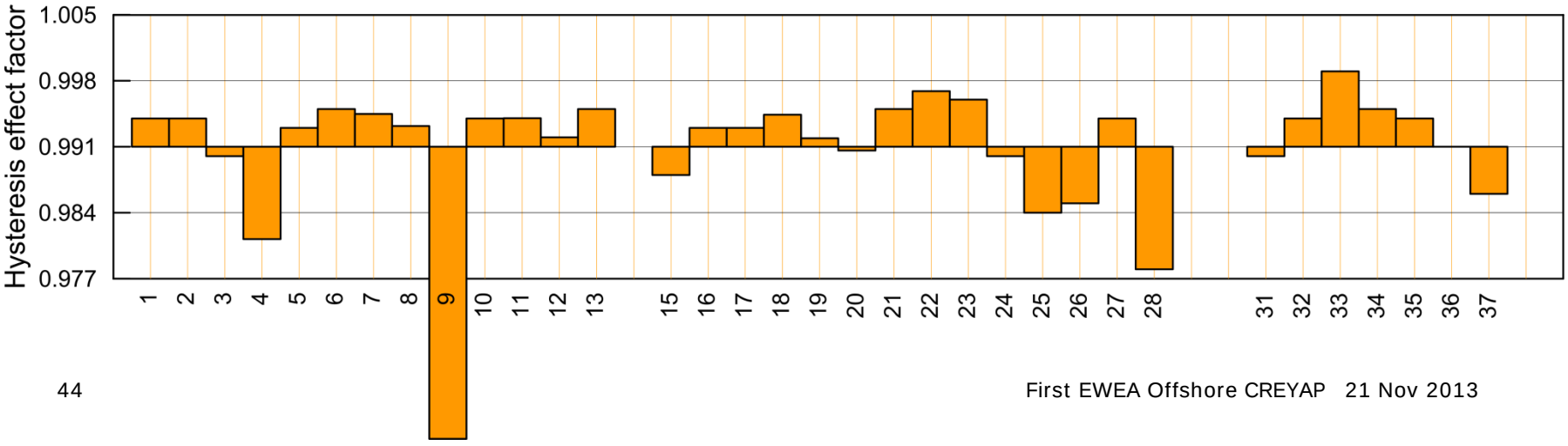
Mean hysteresis effect = 0.991

Standard deviation = 0.007

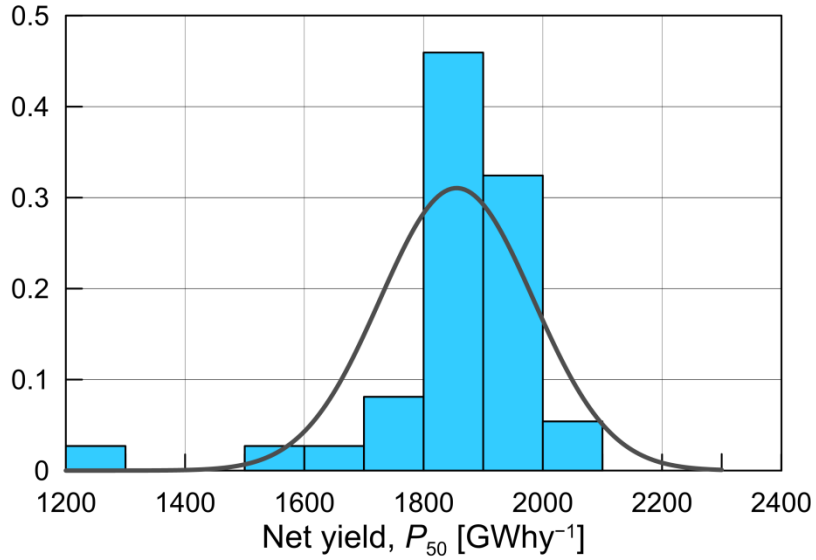
Coefficient of variation = 0.7%

Range = 0.960 to 0.999





Net energy yield of wind farm, P_{50}



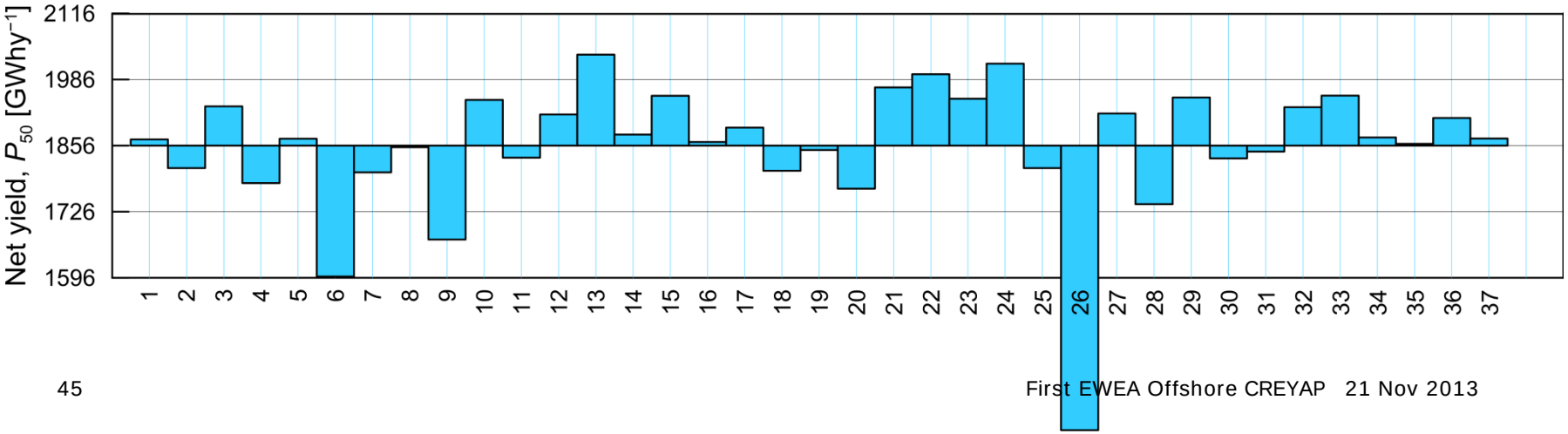
Data points used = 37 (of 38)

Mean net yield = 1856 GWhy^{-1}

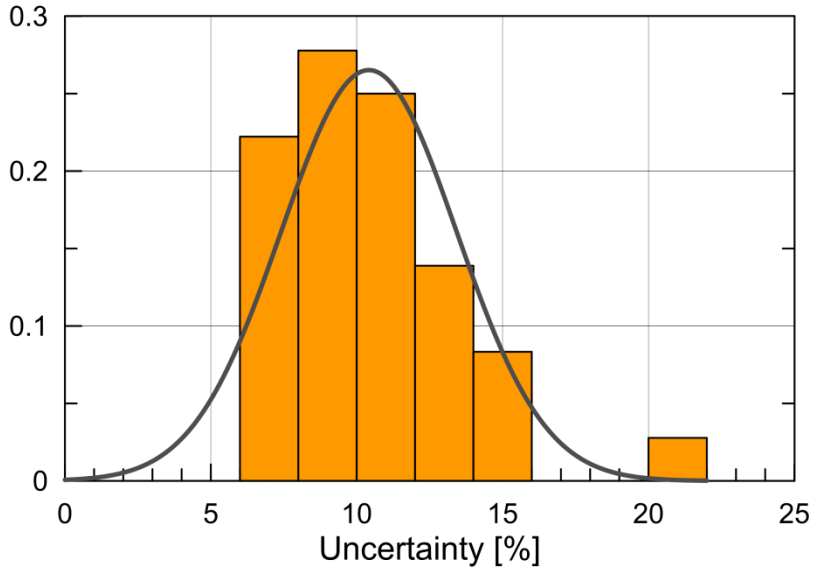
Standard deviation = 130 GWhy^{-1}

Coefficient of variation = 7.0%

Range = 1296 to 2035 GWhy^{-1}



Uncertainty estimates



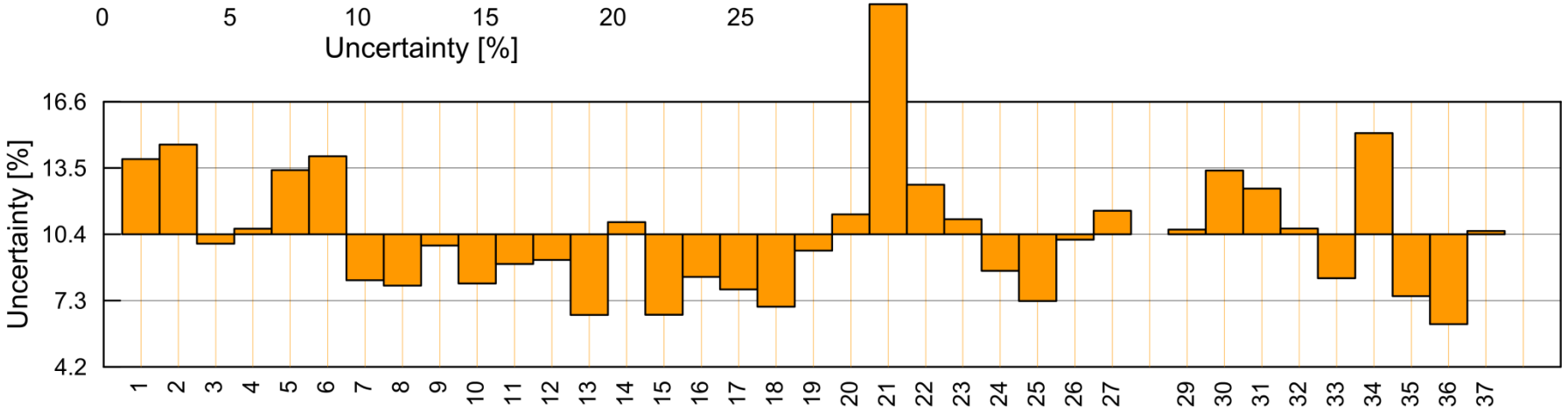
Data points used = 36 (of 38)

Mean uncertainty = 10%

Standard deviation = 3.1%

Coefficient of variation = 29%

Range = 6.2 to 21%



Legend and references

Legend to graphs

- Distribution graphs: histograms + fitted normal distribution. Statistics given next to graph.
- Team result graphs: mean value is base value for histogram, *y*-axis covers a range of ±2 standard deviations, *x*-axis covers teams 1-38.
  No team number indicates 'result not submitted'.
- Box-whisker plots: whiskers defined by the lowest datum still within 1.5 IQR of the lower quartile (Q1), and the highest datum still within 1.5 IQR of the upper quartile (Q3).

For more information on CREYAP Pt. I and II (onshore)

- Mortensen, NG & Ejsing Jørgensen, H 2011, 'Comparison of resource and energy yield assessment procedures'. in: *Proceedings.* EWEA.
- Mortensen, NG, Ejsing Jørgensen, H, Anderson, M & Hutton, K-A 2012, 'Comparison of resource and energy yield assessment procedures'. in: *Proceedings of EWEA 2012 - European Wind Energy Conference & Exhibition.* EWEA - The European Wind Energy Association.
- Mortensen, NG & Ejsing Jørgensen, H 2013, 'Comparative Resource and Energy Yield Assessment Procedures (CREYAP) Pt. II'. in: *Proceedings.* EWEA.